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Progress at the WITCH Experiment towards Weak Interaction Studies

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het behalen van de graad van
Doctor in de wetenschappen
door

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Michaël,
mei 2011

Abstract (English)

A measurement of the β - ν angular correlation in nuclear β decay is a good probe to search for physics beyond the Standard Model, independent of assumptions like parity, charge and time reversal violation. The WITCH (**W**eam **I**nteraction **T**rap for **C**harged **P**articles) experiment will measure this correlation with the aim of further constraining the possible existence of scalar currents in the weak interaction or find a positive indication. The setup is located at ISOLDE/CERN and consists of a double Penning trap system combined with a retardation spectrometer to probe the energy of the recoil ions from the β decay. The shape of the recoil ion energy spectrum allows to determine the β - ν angular correlation coefficient, a . Past experiments have allowed to measure this parameter with a precision of 0.5–1 %. The aim of the WITCH experiment is to measure a with a precision of about 0.5 %.

A first step towards this goal has already been taken in 2006 with the measurement of a recoil ion energy spectrum from the decay of ^{124}In . The complicated decay scheme of this nucleus, however, did not allow to extract the β - ν correlation coefficient. Measurements performed as part of this PhD work showed that the requirements for the prime physics candidate, ^{35}Ar , put even more, stringent technical constraints on the system. To cope with these a major upgrade of the system was found to be necessary. The vacuum has been improved by one order of magnitude ($5 \cdot 10^{-8}$ mbar to $5 \cdot 10^{-9}$ mbar in crucial areas), a control system to automate certain processes of the system was developed, parts of the system were improved and made more flexible and a magnetic shield was installed which allows, in combination with an RFQ buncher, to become independent from other experiments and thus provide significantly more time for testing and optimising the system.

The first trial to measure a recoil ion energy spectrum with ^{35}Ar in 2009 was hampered by a retardation-dependent ionisation effect – due to a Penning-like electron trap in the spectrometer – that was discovered. The effect was characterised with offline measurements, by simulations and with experience gained at other experiments. The solution to this problem is a conductive wire in the centre of this electron trap, effectively absorbing all electrons before they can cause rest gas atoms to be ionised and disturb the measurement.

Further, in preparation for the analysis of a recoil ion energy spectrum from ^{35}Ar decay, systematic effects have been studied in detail. The main effects to

be taken into account relate to the properties of an ion cloud in a Penning trap (i.e. the radioactive source for the experiment), the transport of the recoil ions through the spectrometer and their detection. With the current understanding and operation of the system, the focus for the further investigation of systematic effects will have to lie on the determination of the properties of the ion cloud and the characterisation of the efficiency of the detection surface.

At present, the setup is ready for measuring a good-quality recoil ion energy spectrum from ^{35}Ar decay from which a first value of a can be extracted. The ionisation effect has been solved and important systematic effects have been identified. The study of systematic effects will continue and this should lead to a good determination of a ($\delta a \approx 1\%$) before the CERN shutdown period in 2013.

Abstract (Nederlands)

B - ν angulaire correlatiemetingen in nucleair β -verval zijn gevoelig aan fysica die niet beschreven wordt door het Standaard Model, onafhankelijk van aannames zoals pariteits-, ladings- of tijdsomkeringviolatie. De WITCH opstelling (*Weak Interaction Trap for Charged Particles*) heeft als doel deze correlatie te meten teneinde huidige limieten op het bestaan van mogelijke scalaire stromen in de zwakke interactie te verbeteren of een aanwijzing te vinden voor zulke exotische stromen. De opstelling bevindt zich te ISOLDE aan het CERN en bestaat uit twee Penningvallen gecombineerd met een retardatiespectrometer om het energiespectrum van terugstotende ionen uit β -verval te meten. De exacte vorm van dit energiespectrum laat toe om de β - ν angulaire correlatiecoëfficiënt, a , te bepalen. Dankzij experimenten uit het verleden is deze correlatiecoëfficiënt reeds gemeten met een precisie van 0.5–1 %. Het doel van de WITCH opstelling is om a met een precisie van 0.5 % te meten.

Een eerste stap daartoe werd genomen in 2006 met de meting van een terugstoot-ionenenergiespectrum uit het verval van ^{124}In . Het ingewikkelde vervalschema van deze kern verhinderde echter een grondige analyse zodat de β - ν angulaire correlatiecoëfficiënt niet bepaald kon worden. Als onderdeel van dit doctoraats-onderzoek werden metingen uitgevoerd die aantoonde dat de vereisten voor een meting met ^{35}Ar , de hoofdfysicakandidaat, striktere vereisten stellen aan de opstelling. Om aan deze vereisten te voldoen, was een significante verbetering van de opstelling nodig. Het vacuüm werd verlaagd met een grootteorde ($5 \cdot 10^{-8}$ mbar tot $5 \cdot 10^{-9}$ mbar in belangrijke delen), er werd een controlesysteem ontwikkeld om bepaalde processen te automatiseren, bepaalde onderdelen werden verbeterd en ten slotte werd een magnetische afscherming ontwikkeld die ons toelaat, in combinatie met een RFQ-val, om onafhankelijk te worden van andere experimenten en dus de beschikbare tijd voor testen en metingen gevoelig te verhogen.

De eerste meting van een terugstootenergiespectrum uit het verval van ^{35}Ar in 2009 werd bemoeilijkt door een ionisatie-effect in de spectrometer dat onverwacht opdook, veroorzaakt door een ongewenste Penningval. Dit effect werd gekarakteriseerd door *offline* metingen, door simulaties en door de ervaring opgedaan bij andere experimentele opstellingen. De oplossing voor dit probleem is de installatie van een geleidende draad in het centrum van deze elektronenval zodat alle gevangen elektronen geabsorbeerd worden voordat ze restgas kunnen ioniseren en op die manier het meten van een terugstootenergiespectrum

verstoren.

Als voorbereiding op de analyse van een terugstootenergiespectrum uit het verval van ^{35}Ar werden systematische effecten in detail onderzocht. De belangrijkste effecten waarmee rekening dient gehouden te worden, hebben betrekking tot de eigenschappen van de ionenwolk in een Penningval – wat de radioactieve bron is voor een experiment –, het transport van de terugstootionen door de spectrometer en de detectie hiervan. De huidige hiaten in het onderzoek naar systematische effecten, met behulp van metingen en simulaties, is een gedetailleerde bepaling van de eigenschappen van de ionenwolk en een karakterisatie van de detectie-efficiëntie van het detectoroppervlak.

Op dit ogenblik is de opstelling klaar om een terugstootenergiespectrum van goede kwaliteit te meten uit het verval van ^{35}Ar waaruit a voor de eerste keer met de WITCH opstelling bepaald kan worden. Het ionisatie-effect is onder controle en belangrijke systematische effecten zijn geïdentificeerd. De studie van systematische effecten zal verdergaan en moet leiden tot een goede bepaling van a ($\delta a \approx 1\%$) voor de stillegging van CERN in 2013.

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Introduction

People have been trying to understand the world around us for a long time – in all its different aspects. Concerning physics we believe now that four fundamental forces are present in nature – gravity, the weak interaction, electromagnetism and the strong interaction – and 12 fundamental particles – six quarks and six leptons. These forces and particles interact with each other and are the basic constituents of the world we see around us. The dream of many physicists is to find a theory that can describe these basic building blocks and their interactions. At the moment this has not been realised yet; the best theory to date is the Standard Model. Shortcomings of the theory are e.g. that it cannot describe gravity and that it is not ‘beautiful’; i.e. it contains several free parameters that have to be determined experimentally and cannot be deduced from the theory. Theoreticians, however, continue to work on a more elegant theory which can adequately describe gravity as well and where certain parameters – such as the masses of the known particles – can be deduced from first principles.

From an experimentalist’s point of view, this provides an opportunity to explore the boundaries of the landscape of physics. The fact that the Standard Model is not the ultimate theory, gives us hope that there is physics beyond the Standard Model that is waiting to be discovered. One recent example is the discovery of neutrino oscillations showing neutrinos have a mass where they had previously been assumed to be massless. Another interesting topic of investigation is the search for as yet unobserved exotic – i.e. scalar and tensor – components in the weak interaction. Even though they are not included in the Standard Model, they have not been fully ruled out by experiments. The discovery of an exotic interaction – or any other type of physics beyond the Standard Model – will typically require the Standard Model to be adapted and extended.

The search for physics beyond the Standard Model can be performed at the high-energy frontier – e.g. with the Large Hadron Collider (LHC) at CERN and the Tevatron at Fermilab –, but also in low-energy high-precision experiments. In the former, particles that mediate new interactions can be created in collisions, while in the latter one searches for small departures from the predictions of the Standard Model these particles and new interactions would cause. These low-energy measurements require a high precision and thus a very good control of all systematic effects. For this reason it is beneficial to carry out this type of measurement using different experimental methods. Further, by measuring different observables or using different isotopes and transitions, one can constrain

different types of physics beyond the Standard Model.

The WITCH (**W**eak **I**nteraction **T**rap for **C**harged **P**articles) experiment is one of the experiments searching for scalar interactions. It combines two Penning traps with a retardation spectrometer to measure a recoil ion energy spectrum from β decay. The setup has proven its principle of operation during the ^{124}In run in 2006; a recoil energy spectrum was measured which could be analysed. Analysis of the data was, however, limited by several experimental uncertainties; e.g. the isomer to ground state ratio, a complicated decay scheme, an unknown charge state distribution and the detailed properties of the ion cloud in the decay trap. One year later, in 2007, an experiment was performed with ^{35}Ar which showed that the use of ^{35}Ar (as a noble gas) for this experiment requires much more stringent technical constraints than those that were in place then; the neutralisation rate of ^{35}Ar was high, a lot of (stable) ^{35}Cl contamination was reducing the ^{35}Ar yield in the traps and an ionisation effect prevented the measurement of a recoil ion energy spectrum. To enable a measurement on ^{35}Ar a two-years-lasting upgrade campaign was started.

It has to be emphasised that a medium-scale experiment like WITCH is always a team effort and cannot be controlled by one person alone. In particular, this upgrade campaign has been carried out by a fellow PhD student – Simon Van Gorp – and myself. As such, some parts of this work are equally part of his PhD work [Van Gorp, 2011]. However, each of us has specialised on different aspects of the experiment as well, which will be indicated in the following paragraph. Of course, other people have contributed to this as well; previous team members from before the upgrade campaign [Kozlov, 2005, Coeck, 2007], as well as new team members after the upgrade campaign.

In the first chapter the motivation for the WITCH experiment is described in terms of physics. An overview of the entire system – ranging from the production of the required isotopes to their detection – is given in chapter two. Also the choice of an isotope to do the measurement is described there. These first two chapters, along with information provided in the appendices, give together an overview of all different aspects of the system – i.e. theory, apparatus and software.

In the third chapter an overview of the radioactive runs performed with WITCH over the last few years is given. This provides the historical context for the chapters that are to follow, but also the results of some important key measurements – on the way to a first measurement of the β - ν angular correlation coefficient at WITCH – are presented. Details of the upgrade campaign can be found in chapter 4. It describes the upgrades that were necessary for a measurement with ^{35}Ar , but also upgrades that will facilitate the operation of WITCH in the future: i.e. the installation of a magnetic shield and the construction of an RFQ buncher. The latter two will significantly increase the time available for tests with WITCH, which was until recently limited due to interference of the WITCH stray field with other experiments. This realisation will allow detailed measurements to characterise the Penning traps, which is one of the focusses of Ref. [Van Gorp, 2011]. In chapter 5 the issue of secondary ionisation in the spectrometer will be described based on phenomenological descriptions, mea-

surements and simulations. This ionisation problem has been the major problem that was to overcome during the last years and is, together with the very limited access to stable beams for testing and optimising the system, the main reason why a real β - ν correlation measurement could finally not be performed within the context of this thesis.

Even though the β - ν angular correlation coefficient could not be determined yet, many measurements over the years have allowed to study systematic effects that can occur during a measurement. A list of systematic effects is given in chapter 6, each time supplemented by measurements where possible. Also the systematic uncertainties these effects induce on a have been simulated. Extra details on these simulations can be found in appendix C. Finally, further perspectives for the experiment are given in chapter 7. This includes additional upgrades to the system to further improve the operation and to also give access to interesting other physics opportunities for WITCH.

Additional information for the reader is given in the appendices. One of my personal projects was the development of a control system – based on a framework developed at GSI – for the automatisisation (and optimisation) of several processes at the experiment; e.g. beam tuning by performing voltage scans of the beamline components and trap optimisation by fully computer-controlled power supplies. This is discussed in appendix A by including a published article. Appendix B briefly describes the basics of a Penning trap and how this influences a measurement at WITCH. The study of the exact properties of an ion cloud in a Penning trap is one of the focusses of Ref. [Van Gorp, 2011], however, and will therefore not be treated in detail here.

Chapter 1

Physics Context: The Weak Interaction

The primary physics motivation of the WITCH experiment is to search for scalar admixtures in the weak interaction. The theoretical context and the principle of the measurement method is laid out in this chapter. Also the current state of the search for scalar interactions is presented.

1.1 The Weak Interaction in Nuclear β decay

At the end of the 19th and the beginning of the 20th century several types of radioactive radiation were discovered; α , β and γ radiation. Although they exhibited similar properties – like the typical exponential decay law –, it is now known that β decay is fundamentally different from the other two types of decay because it is a manifestation of the weak interaction. The three most common types of nuclear β decay are

- β^- decay: $n \rightarrow p + e^- + \bar{\nu}_e$,
- β^+ decay: $p \rightarrow n + e^+ + \nu_e$,
- Electron capture (EC) decay: $p + e^- \rightarrow n + \nu_e$,

where p denotes a proton, n a neutron, e^- (e^+) an electron (a positron), and ν_e ($\bar{\nu}_e$) denotes an (anti) electron neutrino. For nuclear β decay the conversion of a proton into a neutron or *vice versa* occurs in a nucleus and thus the nuclear environment will also influence β decay. A clear example of this is the fact that a free neutron will decay with a lifetime of 879.9(9) s [Serebrov & Fomin, 2010], while this will not necessarily happen when the neutron is bound in a nucleus.

In the nuclear environment one can make the distinction between allowed and forbidden β transitions; the allowed transitions are summarised in Table 1.1.

Table 1.1 – Fermi and Gamow-Teller selection rules and operators. Symbols used are the nuclear spin I , the isospin T and the parity π of a nuclear state. The operators refer to: scalar (S), vector (V), tensor (T) and axial vector (A).

	Selection rules	Operators
Fermi	$\Delta I = 0$ $\Delta T = 0$ $\Delta \pi = 0$	S/V
Gamow-Teller	$\Delta I = 0, \pm 1$ ($0 \nrightarrow 0$) $\Delta T = 0, \pm 1$ ($0 \nrightarrow 0$) $\Delta \pi = 0$	T/A

ΔI , ΔT and $\Delta \pi$ denote the difference in spin, isospin and parity respectively between the initial and final states. The two allowed types of transitions are Fermi decays and Gamow-Teller decays.

Nuclear β decay is mediated by a $W^\pm$ boson according to the Standard Electroweak Model, but at low energies it can be approximated by a four-Fermion contact interaction. In analogy with the electromagnetic interaction a Hamiltonian density of the following form was proposed [Fermi, 1934]:

$$\mathcal{H}_F = g_F J_\mu \cdot J^\mu + h.c. \quad , \quad (1.1)$$

with g_F the coupling strength of the weak interaction, and J_μ a weak current containing a hadronic and a leptonic part: $J_\mu = J_\mu^{\text{had}} + J_\mu^{\text{lep}}$.

1.1.1 Weak Interaction Formalism

In 1956 Lee and Yang formulated an extended Hamiltonian density for nuclear β decay including all possible interactions consistent with Lorentz invariance [Lee & Yang, 1956]; thereby triggering a number of experiments that led to the discovery of parity violation ([Wu et al., 1957]),

$$\begin{aligned}
\mathcal{H}_\beta = & (\bar{p}n) (\bar{e} (C_S + C'_S \gamma_5) \nu) \\
& + (\bar{p} \gamma_\mu n) (\bar{e} \gamma^\mu (C_V + C'_V \gamma_5) \nu) \\
& + \frac{1}{2} (\bar{p} \sigma_{\lambda\mu} n) (\bar{e} \sigma^{\lambda\mu} (C_T + C'_T \gamma_5) \nu) \\
& - (\bar{p} \gamma_\mu \gamma_5 n) (\bar{e} \gamma^\mu \gamma_5 (C_A + C'_A \gamma_5) \nu) \\
& + (\bar{p} \gamma_5 n) (\bar{e} \gamma_5 (C_P + C'_P \gamma_5) \nu) \\
& + h.c.
\end{aligned} \quad (1.2)$$

with the tensor operator

$$\sigma_{\lambda\mu} = -\frac{1}{2} i (\gamma_\lambda \gamma_\mu - \gamma_\mu \gamma_\lambda) \quad . \quad (1.3)$$

In this equation the γ_μ 's are the Dirac matrices, $\gamma_5 = \gamma_1 \gamma_2 \gamma_3 \gamma_4$ and $\bar{x} = x \gamma_4$. The interacting particles are leptons and nucleons which are represented by the

leptonic currents e, ν and the hadronic currents p, n respectively. Furthermore the C_X and C'_X are the coupling constants for vector (C_V, C'_V), axial vector (C_A, C'_A), scalar (C_S, C'_S), tensor (C_T, C'_T) and pseudoscalar interaction (C_P, C'_P). Not all of the interactions of Eq. 1.2 occur in nature; this was shown experimentally [Severijns et al., 2006]. Note that in the non-relativistic treatment of nucleons it can be shown that the pseudoscalar hadronic current vanishes and therefore $C_P = C'_P = 0$ and it can be neglected in nuclear β decay. In the Standard Electroweak Model the couplings constants have the following values;

$$\begin{aligned} C_V &= C'_V = 1 \quad , \\ C_A &= C'_A = -1.27293(46) \quad , \\ C_S &= C'_S = 0 \quad , \\ C_T &= C'_T = 0 \quad . \end{aligned} \tag{1.4}$$

$C_T = C'_T = C_S = C'_S = 0$ because these exotic currents have not been observed until now. To incorporate maximal parity violation, $C_V = C'_V$ and $C_A = C'_A$. All of the coupling constants are real because time reversal has not been observed yet in nuclear β decay. It has to be noted that the vector current is conserved in the nuclear medium; this is described as CVC (Conserved Vector Current) [Gell-Mann, 1958] and is reflected in the fact that $C_V = C'_V \equiv 1$. The value of the axial-vector coupling constant is renormalised by the strong interaction, leading to $C_A = C'_A = -1.27293(46)$. This is summarised as PCAC (Partially Conserved Axial vector Current) [Rho, 1974]. Note that this value is only valid for non-nuclear systems (viz. neutron decay). Finally, inside a nucleus the axial-vector coupling is modified by the nuclear environment resulting in $C_A = C'_A \approx 1$ for nuclei with $A > 10$. This is known as the quenching of the axial-vector strength (see e.g. [Towner, 1987]).

1.1.2 Beyond the Standard Electroweak Model

As mentioned before, the coupling constants shown in Eq. 1.4 are determined experimentally. As such, these coupling constants are not determined with infinite precision. Combining data from all correlation measurements (see next section), the 2σ (95.5%) confidence level for all correlation coefficients – under the assumptions that they are real, i.e. no time-reversal violation – is constrained by [Severijns et al., 2006];

$$\begin{aligned} -1.40 &< C_A/C_V < -1.17 \\ 0.87 &< C'_V/C_V < 1.17 \\ 0.86 &< C'_A/C_A < 1.16 \\ -0.065 &< C_S/C_V < 0.070 \\ -0.067 &< C'_S/C_V < 0.066 \\ -0.076 &< C_T/C_A < 0.090 \\ -0.078 &< C'_T/C_A < 0.089 \quad . \end{aligned} \tag{1.5}$$

Note that these limits are not in contradiction with the Standard Electroweak Model. However, the situation leaves a lot of room for potential non-Standard

Model physics. The main goal of the WITCH experiment is to further constrain the limits on the scalar couplings or to search for scalar admixtures in the observed weak interaction currents. Fermi decays are mediated by vector currents, while Gamow–Teller decays are mediated by axial vector currents. A potential scalar interaction has a structure similar to the vector interaction, so that it will only show up in Fermi decays. The same is true for tensor interactions and axial vector interactions. To efficiently search for scalar admixtures in the weak interaction, one thus has to look in a pure Fermi decay. The observed quantities that allow extracting information on exotic currents are described in the following section.

1.1.3 Correlation Measurements

From the Hamiltonian density a distribution formula for the neutrino and β direction, β polarisation and β energy can be derived, as is done in [Jackson et al., 1957]:

$$\begin{aligned} \omega(\boldsymbol{\sigma}|E_\beta, \Omega_\beta, \Omega_\nu)dE_\beta d\Omega_\beta d\Omega_\nu = & \\ \frac{F(\pm Z, E_\beta)}{(2\pi)^5} p_\beta E_\beta (E_0 - E_\beta)^2 dE_\beta d\Omega_\beta d\Omega_\nu \frac{\xi}{2} & \\ \left\{ 1 + a \frac{\mathbf{p}_\beta \cdot \mathbf{p}_\nu}{E_\beta E_\nu} + b \frac{m_\beta}{E_\beta} + A \frac{\langle \mathbf{J} \rangle}{J} \cdot \frac{\mathbf{p}_e}{E_e} \right. & \\ \left. + \boldsymbol{\sigma} \cdot \left[G \frac{\mathbf{p}_\beta}{E_\beta} + H \frac{\mathbf{p}_\nu}{E_\nu} + R \left(\frac{\langle \mathbf{J} \rangle}{J} \times \frac{\mathbf{p}_e}{E_e} \right) + \dots \right] \right\}. & \quad (1.6) \end{aligned}$$

More extended versions of this distribution function can be found in the same reference. In the equation $E_{\beta,\nu}$, $\mathbf{p}_{\beta,\nu}$ and $\Omega_{\beta,\nu}$ refer to the energy, momentum and emission angle of the β particle and neutrino respectively, where E_0 is the total energy available in the decay. The polarisation vector of the β particle is given by $\boldsymbol{\sigma}$. The lower (upper) sign in the Fermi function $F(\pm Z, E_\beta)$ refers to β^- (β^+) decay. The Fermi function itself is a final state correction to the β spectrum due to the electromagnetic interaction. The mass of the electron is denoted by m_β . The degree of nuclear polarisation is given by $\frac{\langle \mathbf{J} \rangle}{J}$, where $\mathbf{J}$ denotes the nuclear spin vector. The various correlation coefficients are represented by a , b , A , G , H and R . The common factor ξ is not a correlation coefficient but contains the coupling constants in the following way:

$$\begin{aligned} \xi = & |M_F|^2(|C_S|^2 + |C'_S|^2 + |C_V|^2 + |C'_V|^2) \\ & + |M_{GT}|^2(|C_A|^2 + |C'_A|^2 + |C_T|^2 + |C'_T|^2) \quad , \quad (1.7) \end{aligned}$$

with M_F and M_{GT} the Fermi and Gamow–Teller transition matrix elements respectively. The correlation coefficients contain the information about the weak interaction coupling constants and depend on different combinations of these. The combination of spin and momentum vectors associated with each correlation coefficient determines what kind of measurement is required to determine that particular correlation coefficient. If one would for instance only measure the polarisation of the β particle and its momentum, all terms vanish, except for the one with the G and the b correlation coefficient in Eq. 1.6. All terms that

contain different or more observables than those two – i.e. β polarisation and momentum – are then integrated out of the equation. The Fierz interference term, b , is present for all correlation measurements but is zero in the Standard Model (see Eq. 1.10).

1.2 β - ν Angular Correlation

If one measures the angle between the neutrino and β momentum, the so-called β - ν angular correlation coefficient a can be measured;

$$\begin{aligned} a\xi &= |M_F|^2 \left[|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2 \mp \frac{\alpha Z m_e}{p_\beta} 2\text{Im}(C_S C_V^* + C'_S C_V'^*) \right] \\ &+ \frac{|M_{GT}|^2}{3} \left[|C_T|^2 + |C'_T|^2 - |C_A|^2 - |C'_A|^2 \pm \frac{\alpha Z m_e}{p_\beta} 2\text{Im}(C_T C_A^* + C'_T C_A'^*) \right] \end{aligned} \quad (1.8)$$

In practice also the Fierz interference term will be measured, so that the actual experimental observable will be

$$\tilde{a} = \frac{a}{1 + \frac{m_e}{E_\beta} b}, \quad (1.9)$$

with

$$b\xi = \pm 2\Gamma \text{Re} \left[|M_F|^2 (C_S C_V^* + C'_S C_V'^*) + |M_{GT}|^2 (C_T C_A^* + C'_T C_A'^*) \right] \quad (1.10)$$

and ξ given by Eq. 1.7. From Eq. 1.8 it can be seen that the β - ν correlation depends quadratically on exotic currents. This is a disadvantage of the method on the one hand as the influence of potential exotic currents on a will be reduced. On the other hand, the β - ν correlation is independent of parity, charge or time reversal violation effects, unlike other correlations that can trivially become zero for certain conditions.

1.2.1 Measurement Method

For a measurement of the β - ν angular correlation coefficient one needs to measure the momentum of the neutrino and the β particle and the angle between those two momenta. Obviously it is not practical to measure the momentum of the neutrino. Therefore, the kinematics of the decay needs to be reconstructed to determine the neutrino momentum; this can be done by observing the recoiling daughter nucleus after the decay by conservation of energy and momentum (see Fig. 1.1).

This can be done in a coincidence measurement, where the (fast) β particle serves as trigger for the detection of the recoil ion. The energy and angle of the recoil ion are deduced from the time-of-flight (after the β) and the position of the detected recoil ion. The angular correlation coefficient a can thus be deduced.

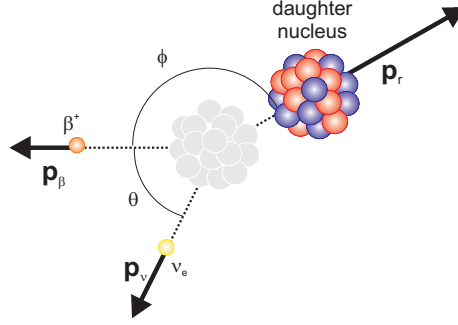


Figure 1.1 – Kinematics in the determination of the β - ν angular correlation coefficient. The angle θ is the angle between the momenta of the (anti) neutrino and the β particle, and is important for the determination of the β - ν angular correlation coefficient (see Eq. 1.11). The angle φ is the angle between the momenta of the β particle and the recoiling nucleus. The momenta p_r , p_β and p_ν are the momenta of the recoiling nucleus, the β particle and the (anti) neutrino, respectively. Taken from [Coeck, 2007].

A measurement of the recoil ion energy also yields enough information to deduce a . This can be done indirectly by measuring secondary radiation (see next section) or by directly measuring the energy of the daughter nucleus as is the case in WITCH. The shape of the recoil ion energy spectrum is influenced by the exact value of a as is shown by writing the distribution formula $W(\theta)$ in terms of $\tilde{a}$,

$$W(\theta) = 1 + \frac{p_\beta \cdot p_\nu \cdot \cos(\theta)}{E_\beta \cdot E_\nu} \tilde{a} \quad , \quad (1.11)$$

with θ the angle between the neutrino and the β particle. For $a \neq 0$ the angle between the β particle and the neutrino will not be randomly distributed. For small values of a – e.g. in the case of pure scalar currents $a = -1$ – most decays will have a relatively large θ , close to 180° meaning that the β particle and the neutrino will be emitted back-to-back. For large values of a the angle θ will be generally small. This influences a recoil ion energy spectrum as shown in figure 1.2. Please note that at WITCH not a differential, but an integral energy spectrum is measured. Systematic effects altering the shape of the recoil ion energy spectrum are discussed in chapter 6.

1.2.2 State of the Art

Several measurements of the β - ν angular correlation coefficient have been performed in the past already, while others are still under development or in the data-taking process.

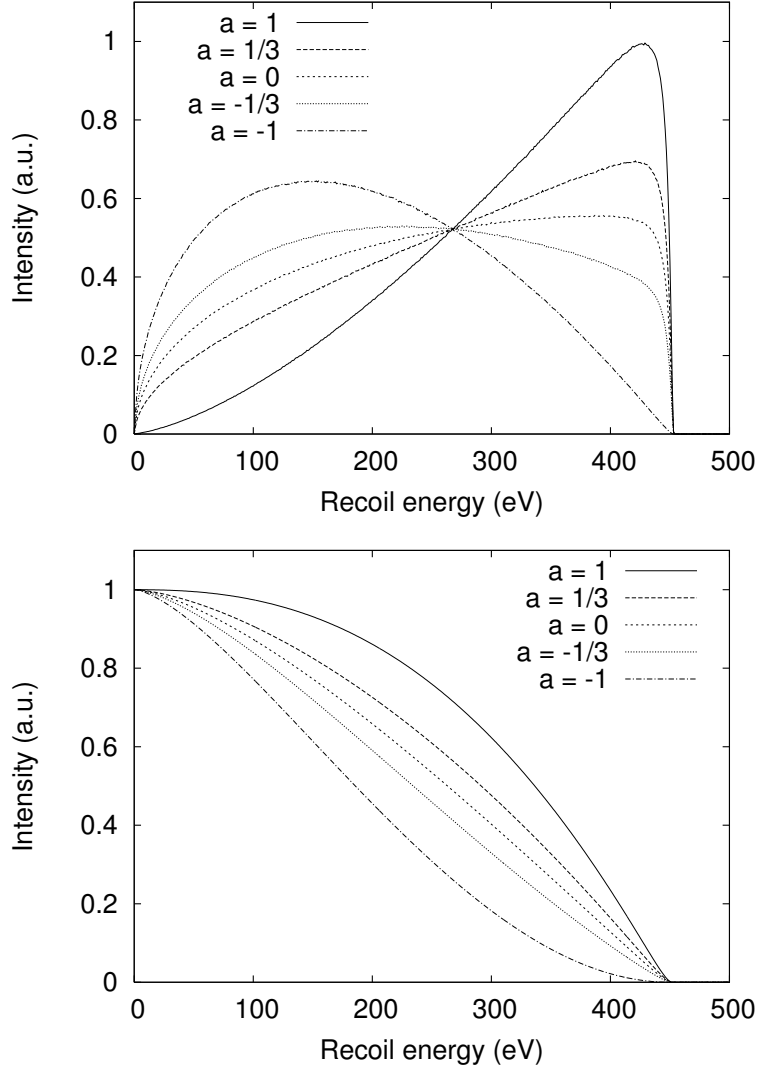


Figure 1.2 – Top: Differential recoil ion energy spectrum from the decay of ^{35}Ar and for different values of the β - ν angular correlation coefficient a . **Bottom:** The integral spectra for the same situations. Please note that these spectra are shown for a large range of values for a . Potential deviations from the expected Standard Model spectrum shape (e.g. corresponding to $\Delta a = 0.005$) will be much smaller and (almost) not visible in these graphs. Taken from [Coeck, 2007].

Without traps

The most precise measurement sensitive to tensor currents has been performed with ${}^6\text{He}$ at Oak Ridge [Johnson et al., 1963]. A value of $\tilde{a} = -0.3343(30)$ was measured, which is the most precise one for a Gamow–Teller decay up till now.

A very precise determination of a in a pure Fermi decay comes from the superallowed decay of ${}^{32}\text{Ar}$. The recoil ion energy was deduced from the effect on the subsequent proton decay. An initial measurement is reported in Ref. [Schardt & Riisager, 1993] where the recoil energy was extracted from the Doppler broadening of the protons. This was later improved in a new experiment that is reported in Ref. [Adelberger et al., 1999]. A value of $\tilde{a} = 0.9989 \pm 0.0052^{\text{stat}} \pm 0.0039^{\text{syst}}$ was obtained. A better determination of the mass of ${}^{32}\text{Ar}$ changed the central value to $\tilde{a} = 1.0050$ [Blaum et al., 2003]. However, a re-analysis of the data is needed to obtain the new systematic error uncertainty. This is currently ongoing [Garcia, 2010].

A more recent experiment – aSPECT – aims at the determination of a from neutron decay [Glück et al., 2005]. It uses a spectrometer similar to the one used in WITCH (see section 2.4). Unlike the experiments with trapped radioactive ions (see below), the decay products are intercepted from a cold neutron beam which is produced at the ILL in Grenoble. A first determined value for a is $\tilde{a} = -0.1151 \pm 0.0040^{\text{stat}}$ [Baeßler et al., 2008]. Systematic uncertainties are under investigation at the moment. An issue for the determination of a in neutron decay is the correct determination of the neutron half-life [Serebrov & Fomin, 2010], which limits the accuracy of the determination of a .

With traps

Particle traps have opened up new possibilities for correlation measurements, spawning a lot of new experiments in the last ten years.

The most precise determination of a in a Fermi decay was performed at TRIUMF on ${}^{38\text{m}}\text{K}$ with the help of a magneto-optical trap (MOT) [Gorelov et al., 2005]. The recoil ions were detected in coincidence with the β 's; this allows for a reconstruction of their energy by a time-of-flight measurement. They obtained $\tilde{a} = 0.9981 \pm 0.0030^{+0.0032}_{-0.0037}$, which is in agreement with and has similar uncertainties as [Adelberger et al., 1999], even though a completely different experimental method was used.

Another measurement with a MOT was performed at Berkeley on ${}^{21}\text{Na}$ [Scielzo et al., 2004]. They obtained $\tilde{a} = 0.5243 \pm 0.0091$ which deviated by 3σ from the predicted Standard Model value of $a = 0.5587(27)$ [Severijns et al., 2008]. The authors of the paper already note that the exact value of a depends on the number of atoms in the trap. This was later explained by the formation of molecular sodium. An improved measurement was done by measuring recoil ions in coincidence with shake-off electrons; the increased sensitivity allowed for using smaller trap loads thus avoiding the formation of molecules. The obtained value is $\tilde{a} = 0.5502(60)$, which is in agreement with the Standard Model

[Vetter et al., 2008].

The LPCTrap is a transparent Paul trap located at LPC-Caen [Ban et al., 2005]. This has provided a new measurement on ${}^6\text{He}$ to extract information on tensor currents. The feasibility of the technique has been proven [Flécharde et al., 2008], and the final analysis is under way. LPCTrap is the first ion trap that was used for a β - ν correlation measurement. In principle a measurement on any produced isotope can be performed with ion traps, unlike the MOTs which are limited to the alkali (earth) metals.

Chapter 2

Overview of the WITCH Experiment

In this chapter an overview of the WITCH setup is presented, both in technical and conceptual terms. First an overview of the components of the setup, starting from the production of the isotopes until their detection, is given. This is followed by a description of a typical experimental cycle, the data-acquisition and analysis procedure. Finally, the constraints for selecting isotopes well suited for experiments at WITCH are discussed.

2.1 Radioactive Source Production

2.1.1 ISOLDE

The WITCH experiment is located at the ISOLDE facility in CERN. ISOLDE is a facility dedicated to the production of a broad range of radioactive isotopes which are used for a large variety of experiments [Kugler, 2000]. Most experiments are situated in the field of nuclear and solid-state physics, but also biophysics experiments are performed. The radioactive beams are created by shooting proton bunches with an energy of 1.4 GeV, a time separation of 1.2 s and an intensity of about $2\mu\text{A}$, coming from the Proton-Synchrotron Booster accelerator, onto a target at ISOLDE.

The protons cause different types of reactions when interacting with the various types of targets; radioactive ions can be created via fission, spallation or fragmentation. The target is typically at a high temperature of the order of 1000°C causing the created elements to diffuse out of it. The speed of this diffusion depends on the physical and chemical properties of the element. Noble gases for instance will diffuse rather quickly out of the target, while rare earth metals will need a longer time: e.g. ^{35}Ar vs. ^{144}Eu .

Once they have diffused out of the target, the isotopes have to be ionised for

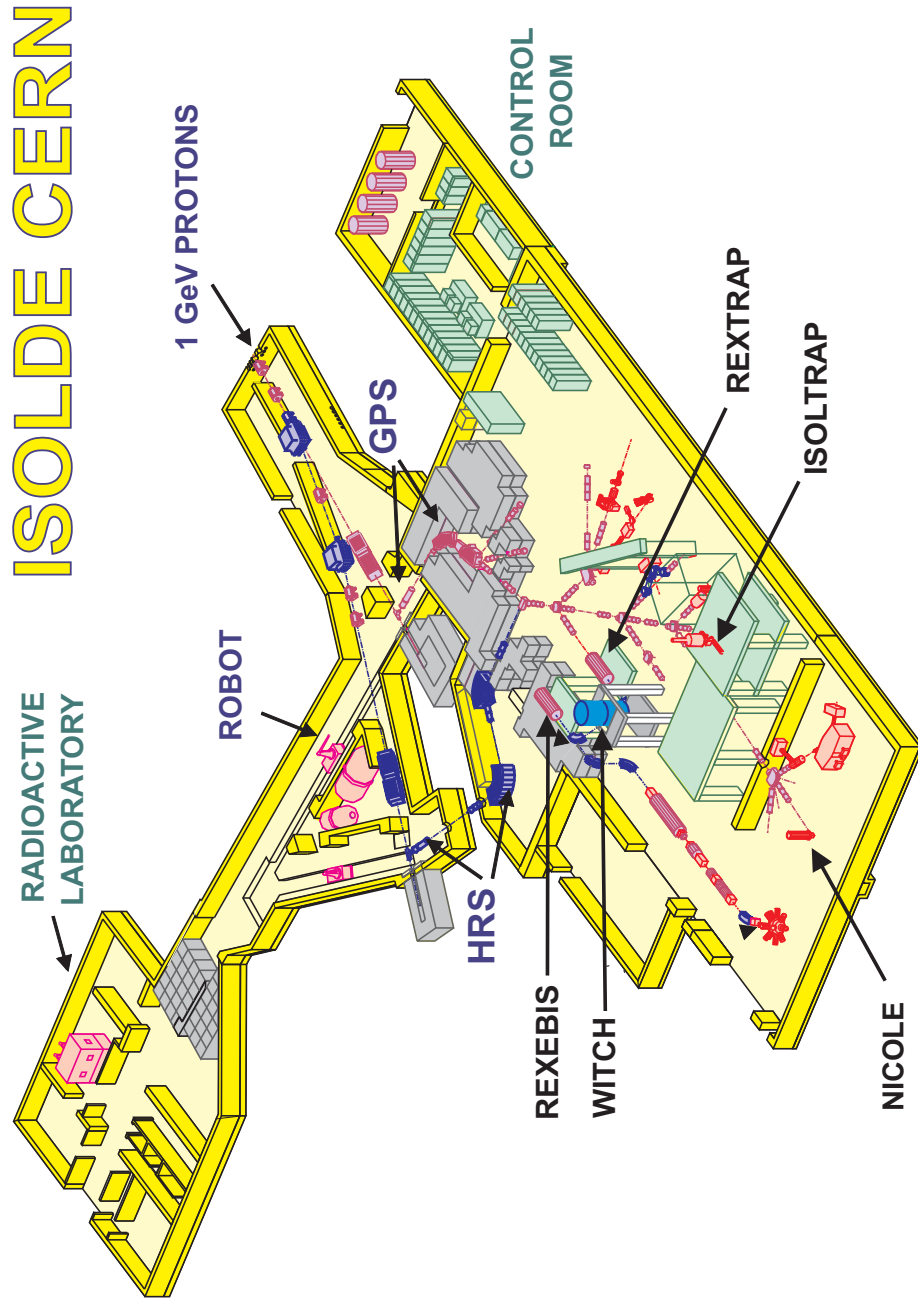


Figure 2.1 – The ISOLDE facility at CERN. This picture is slightly outdated as the experimental hall has been extended in the meantime. However, it does correctly show the position of WITCH in the ISOLDE hall with relation to other experiments.

electrostatic extraction – typically to a 1^+ charge state. This can be done with a surface ionisation source, by electron impact in a hot plasma (e.g. VADIS [Penescu et al., 2010]) or by resonant laser ionisation [Fedosseev et al., 2003]. Once ionised, the radioactive beam is typically accelerated to 60 keV, but for REX and – thus WITCH – the ISOLDE beam is accelerated to 30.2 keV. Then the beam goes through a mass separator before it is sent to the experimental area. Two separators are available: the General Purpose Separator (GPS) and the High Resolution Separator (HRS). Each separator also has its own target. The mass selectivity ($m/\Delta m$) of the two separators is 500 for the GPS and 5000 for the HRS. In general it is not possible to perform isobaric separation. Element selectivity (same Z) can be obtained by using resonant laser ionisation. After mass separation the radioactive ion beams are sent into the experimental area.

2.1.2 REXTRAP

REXTRAP [Ames et al., 2005] is the first component of the REX-ISOLDE facility [Habs et al., 2000]. Its main purpose is to bunch the continuous radioactive ion beam from ISOLDE. This is necessary for the REXEBIS charge breeder [Ames et al., 2004] and for experiments with WITCH. REXTRAP is a Penning trap in a 3 T magnetic field at a potential of 30 kV. The potential inside the trap is such that ions from ISOLDE can continuously enter with a kinetic energy of 200 eV, but cannot escape the trap anymore due to buffer gas collisions. The buffer gas is neon or argon gas at a relatively high pressure ($\sim 10^{-3}$ mbar). Collisions with the buffer gas will reduce the axial energy of the radioactive ions sufficiently to keep them in the trap. With the ions in the axial centre of the trap further manipulations, such as radial cooling with a sideband excitation, but also separation of different ion species can be performed. The latter is still under investigation [Sturm et al., 2009]. When the ion bunch is ready it can be sent either to REXEBIS or to WITCH. For REXEBIS ion bunches are typically created every 20 ms (i.e. at 50 Hz) while for WITCH the repetition rate is of the order of 1 Hz. Moreover, the ejection potential in REXTRAP is also different for WITCH operation, i.e. the ejection potential is steeper to have a lower time spread of the ion bunch. The optimisation of REXTRAP for WITCH operation has been investigated in Ref. [Coeck, 2007]. When the ions leave REXTRAP they have a kinetic energy of 30 keV because the WITCH system is at ground potential while REXTRAP is elevated to 30 kV. For testing purposes in REX-ISOLDE and WITCH, stable ions can be obtained from a surface ionisation source [Ghalambor Dezfali, 1996] which is located not far from the trap entrance.

2.2 Beamlines

The main purpose of the beamline from REXTRAP to the WITCH Penning traps is to reduce the ions' kinetic energy from 30 keV to close to zero kinetic

Abbreviation	Function
HB	Horizontal beamline
VB	Vertical beamline
IS	Ion source in HBL
KICK	Kickers
BEND	Benders
STEE	Steerers
EINZ	Einzel lens electrode
RETA	Retardation electrode
PDT	Pulsed drift tube
DRIF	Drift electrode
MCPD	MCP detector
FCUP	Faraday cup detector
PIN	Pin diode detector
DIAP	Diaphragm
IONS	Cross beam ion source

Table 2.1 – Naming conventions used in figures 2.2 and 2.3.

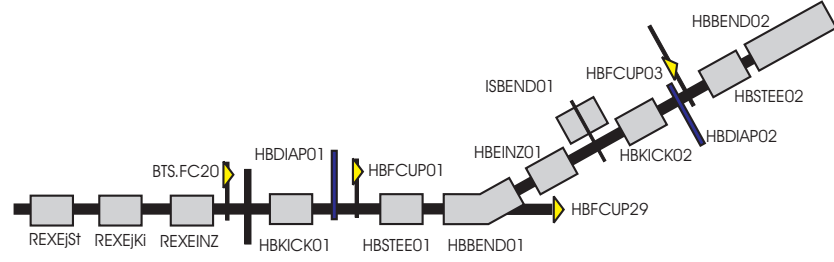


Figure 2.2 – A representation of the electrodes and the beam diagnostics in the horizontal beamline following the naming conventions of Table 2.1. Also some elements of the REXTRAP beamline are given; REXEjSt for ejection steerer, REXEjKi for ejection kicker, REXEINZ for an einzel lens electrode and BTS.FC20 which is the last Faraday cup before the WITCH beamline.

energy and guide them with minimal losses into the Penning traps. There are two main components: the horizontal beamline (HBL) and the vertical beamline (VBL). Most electrodes in the beamline are electrostatic elements; general naming conventions are listed in table 2.1. The design of the electrodes in the beamlines has been discussed in detail in Ref. [Delauré, 2004].

2.2.1 Horizontal Beamline

The ion bunches coming from REXTRAP enter the WITCH setup in the horizontal beamline (Fig. 2.2) with a kinetic energy of 30 keV. The main purpose of this beamline is to transfer the ions from REXTRAP to the vertical beamline without losses. The main components of the HBL are two kicker and bender pairs and an einzel lens electrode. The first kicker and bender pair (HBKICK01

and HBBEND01) bends the beam over an angle of 29° , while the second kicker and bender pair (HBKICK02 and HBBEND02) changes the beam direction over an angle of 90° so that it can be injected in the vertical beamline. Each electrostatic bender consists of two spherical electrodes. They do not cover the full angle of 29° or 90° without the kickers. This makes it possible to install other setups behind the kickers. One could install, for instance, behind the 29° kicker a tape station system to monitor the radiation and thus the radioactive ion yield.

Another important component in the system is the einzel lens electrode (HBEINZ01). Additionally there are two pairs of steerers (HBSTEE01 and HBSTEE02) present in the horizontal beamline, one up/down pair and one left/right pair, to correct the beam direction. All electrodes have a static voltage applied to them. The exception is usually one of the kicker electrodes of the 29° bender. The chosen electrode receives the correct voltage for a short time, $1 - 5 \mu\text{s}$ typically, which allows selecting only a part of the ion bunch coming from REXTRAP – this is referred to as the beamgate. This can be used as a time-of-flight separation for unwanted ion species, most notably ionised REXTRAP buffer gas, so as to have a ion bunch with a single mass into the system. Additionally the time-structure of the ion bunch can be optimised; the time-length of the bunches should be lower than $2.5 - 4 \mu\text{s}$ for an efficient operation of the pulsed drift tube. When the correct voltage is not applied the ion bunch is obviously not transferred further in the system.

A surface ionisation source is attached to the horizontal beamline which has been extended with an RFQ buncher to provide offline ion bunches for the WITCH experiment (see section 4.3.1 and Ref. [Traykov, 2011]). This ion source makes it possible to perform tests independently of the REXTRAP system. The ion source itself is at a potential of 30 kV so that the created ions have a kinetic energy of 30 keV upon entering the horizontal beamline. To guide the ions from the ion source into the horizontal beamline an additional 90° bender (ISBEND01) is present, which can be moved in and out of the beamline.

2.2.2 Vertical Beamline

The vertical beamline (Fig. 2.3) is the final step between REXTRAP and the Penning traps of WITCH. In this part of the system two important actions are performed. First, the kinetic energy of the ion bunch is lowered from 30 kV to ~ 0 V. Secondly, the ion bunch is injected into the magnetic field.

The reduction of the kinetic energy can be achieved in several ways. In some experiments, e.g. REXTRAP, this is realised by lifting the whole setup to a potential of 30 kV, but at WITCH the option of a pulsed drift tube (PDT) was chosen. This electrode switches over a range of 30 kV when the ion bunch is travelling through it. In practice the ions enter the PDT when it is at 21 kV, thus having a kinetic energy of 9 keV in the PDT. The time required to pulse down to -9 kV is of the order of $1 \mu\text{s}$. Right before the ions leave the pulse drift tube they still have a kinetic energy of 9 keV but a total energy of 0 keV. The potential of the electrodes behind the PDT goes from -5 kV to about ground

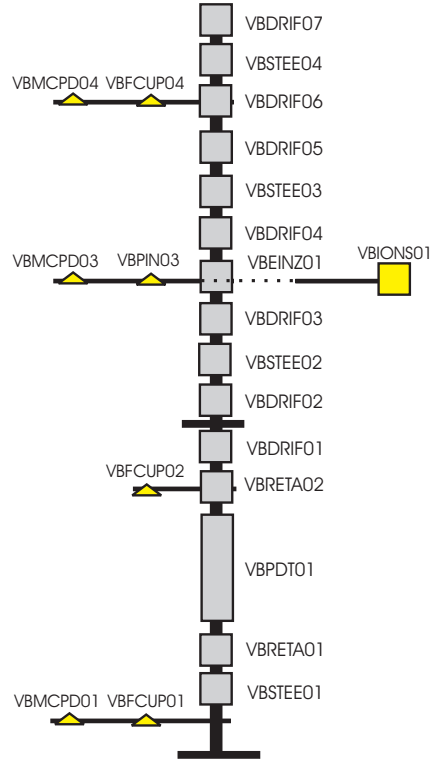


Figure 2.3 – A representation of the electrodes and the beam diagnostics in the vertical beamline following the naming convention of Table 2.1. Details of the MCP detectors and Faraday cups can be found in section 2.2.3. VBPIN03 is a set of pin diodes as explained in section 4.2.3. Beam diagnostics that are located at the same position as an electrode can be inserted via a push-pull mechanical feedthrough.

potential right before the traps; this way the ions arrive at the traps with a low kinetic energy of $\mathcal{O}(100\text{ eV})$. Recent improvements to the pulsed drift tube electronics have lead to the possibility of operating the PDT at 5 Hz. Details and some considerations involved in the upgrade are described in section 4.2.1. The detailed operation of the PDT is described in Ref. [Coeck et al., 2007a].

An additional difficulty is the injection of the relatively slow ions into the stray magnetic field of the Penning traps. The injection occurs between the two last beams diagnostic feedthroughs in the VBL (see figure 2.3). When the transversal component of the velocity of the ion bunch is too large – in comparison to the longitudinal component – they will be reflected off this magnetic field; this is called a magnetic mirror. For a maximum injection efficiency into the magnetic field, the beam has to be steered as parallel as possible to the field lines. For this purpose three steerer quadruplets are present in the VBL above the PDT.

2.2.3 Beam Diagnostics and Tuning

Diagnostic tools

Two types of diagnostic devices are used in the WITCH beamlines; Faraday cups and MicroChannel Plate (MCP) detectors. Their location can be seen in figures 2.2 and 2.3.

A Faraday cup is basically a metal plate which is slid into the beam path with the (ion) current being measured by an electrometer. A Faraday cup is not a very sophisticated device, but nonetheless it allows to measure absolute efficiencies of the beam tune. The drawback is that it cannot be used for a low number of ions. The practical detection limit for an electrometer is of the order of 1 pA, which roughly corresponds to $6 \cdot 10^6$ particles per second. This number of ions corresponds to a full trap load of REXTRAP and is most of the time not being used for tuning. As a consequence it is hard to detect a single ion bunch originating from REXTRAP; this problem can be solved by using a higher repetition rate. Unfortunately this excludes the use of the PDT, the repetition rate of which is limited to 5 Hz. As a result, the Faraday cups in the horizontal and vertical beam lines, are mainly used to tune the 30 keV ions.

In order to tune the pulsed-down low-energy ions, diagnostic MCP detectors are used. MCPs have many small channels in them. Incoming particles can create an electron avalanche, much like in a photomultiplier tube. The resulting electrons from this avalanche are picked up by a conducting plate behind the MCP: the anode. This creates a current pulse with a length of the order of 10 ns. A bunch of ions is thus not detected as a single pulse, but rather as a series of short – possibly overlapping – pulses. For a typical ion bunch at WITCH with a length of 2–4 μs the overlap of signals will already happen with ~ 200 ions. Using these short pulses to quantify the number of ions is not really possible. For a continuous beam or a bunch containing few ions the number of ions can be measured, but for a high intensity ion bunch this is hard [Coeck et al., 2006]. One data-acquisition method to overcome this is to use an oscilloscope and a high resistive termination to amplify the MCP signal ([Coeck, 2007, p. 57] or

Fig. A.6). The many short and low-amplitude pulses are then transformed into one big pulse with large amplitude. This amplified signal can easily be seen on an oscilloscope and used for tuning. The height of the signal is an indication for the amount of ions impinging on the MCP detector, but it does not give the actual number of detected ions due to saturation effects. Calibrating the MCP detectors as a function of the bias voltage and the number of ions is required to maximise the information one can obtain from them. The positions of the MCP detectors are indicated in Fig. 2.3. An additional diagnostic MCP is, finally, present in the spectrometer (see Fig. 2.4) to monitor ions that pass through the traps or are ejected from the traps.

Some additional tools exist at WITCH to measure beam profiles: diagnostic apertures and segmented anodes for the MCP ([Coeck, 2007, p. 58]). Diagnostic apertures are a series of holes with various sizes - ranging from 8 mm to 20 mm - and slits in horizontal and diagonal direction with a width of 1 mm, that can be inserted into the beamline to obtain the beam profile. In the past they were used to characterise the beam. Currently they are only in use in the horizontal beamline for diagnostics of problems. The system with segmented anodes is currently removed due to vacuum considerations, but it might be used again in the future.

Tuning

The Faraday cups and diagnostic MCP detectors are the eyes and ears for the beamline tuning. Currently beam tuning is done by changing voltages on the electrodes and monitoring the effect this has on the beam intensity. This is done in an automated fashion by a scanning utility of the computer control system (see section A.4.3). In the design and commissioning phase of the setup a set of voltages was simulated in SimIon [sim, 2010]. In practice tuning is started from old settings that yielded good transmission. Once a signal is seen on the beam diagnostics, optimisation can start. During the optimisation all diagnostic tools are used, going step by step downstream in the system. The final step in the tuning consists of looking at the diagnostic MCP in the spectrometer and optimise the signal of trapped ions on that detector.

Transport Efficiency

From 2004 Ref. [Kozlov, 2005] to Ref. [Coeck, 2007] the transport efficiency from REXTRAP to the cooler trap was improved dramatically; it was increased from 0.08–0.8% to 10–20%. This was achieved by a systematic study of the beam transport using the diagnostic MCPs (see section 2.2.3) and also by tuning the properties of the ion bunches (i.e. the time structure) coming from REXTRAP so as to increase the efficiency of the pulsed drift tube to close to 100%. Another important factor in the improvement of the transport efficiency was realised by the use of early versions of a control system (see chapter A) which allowed to perform automated systematic scans of the voltages on the beamline electrodes. The remaining bottleneck in the beam tuning is the injection of the ion bunches

Table 2.2 – Voltage settings of the beamline electrodes. The second column lists the originally simulated settings adapted to 30 keV beams (from [Delaure, 2004] and modified in [Coeck, 2007]). In the third and fourth columns actual settings used in two different runs with ^{35}Ar are shown.

Electrode	Simulated voltages (from [Coeck, 2007]) (V)	^{35}Ar run 2007 (V)	^{35}Ar run 2009 (V)
HBKICK01L	-1100	-1235	-1190
HBKICK01R	1100	1235	1190
HBSTEE01U	0	0	20
HBSTEE01D	0	0	-20
HBBEND01L	-2186	-2132	-2090
HBBEND01R	2186	2132	2090
HBEINZ01	5750	13500	13500
HBKICK02U	-1100	-1250	-1210
HBKICK02D	1100	1250	1210
HBSTEE02L	0	-10	-25
HBSTEE02R	0	10	25
HBBEND02U	-2186	-2186	-2186
HBBEND02D	2186	2186	2186
VBSTEE01D	0	0	-79
VBSTEE01U	0	0	79
VBSTEE01L	0	0	-5
VBSTEE01R	0	0	5
VBRETA01	20000	0	0
VBPDT01P	26000	21000	21000
VBPDT01N	-4000	-9170	-9120
VBRETA02	-1250	-5200	-4000
VBDRIF01	-1000	-5100	-3000
VBDRIF02	-750	-2050	-2000
VBSTEE02D	-750	-1910	-1820
VBSTEE02U	-750	-1910	-1780
VBSTEE02L	-750	-1905	-1815
VBSTEE02R	-750	-1895	-1785
VBDRIF03	-750	-2050	-1800
VBEINZ01	-750	-1510	-950
VBDRIF04	-200	-1500	-1400
VBSTEE03D	-750	-1230	-1200
VBSTEE03U	-750	-1230	-1200
VBSTEE03L	-750	-1245	-1200
VBSTEE03R	-750	-1275	-1200
VBDRIF05	-750	-1200	-1200
VBDRIF06	-750	-1200	-320
VBSTEE04D	-750	-450	-415
VBSTEE04U	-750	-450	-385
VBSTEE04L	-750	-450	-400
VBSTEE04R	-750	-450	-400
VBDRIF07	-750	-450	-400
VBDRIF08-11	-750	-50	-250
VBDRIF12	-750	-10	0

into the magnetic field which has an efficiency of the order of 10–20 % at the moment. This will be further increased by investing more time in beam tuning, whereas in the past years, other items (i.e. the optimisation of the Penning traps) had priority in view of the limited time that was available for tuning with stable beams.

2.3 Penning Traps

The WITCH experiment contains two Penning traps. A Penning trap is an ion trap in which the radial confinement is realised by a static dipole magnetic field, and the axial confinement is realised by a static quadrupole electric field. In the WITCH setup a first trap, the cooler trap, is used to capture and cool the ion bunch from REXTRAP. This cooled ion cloud is then transferred to a second trap, the decay trap, which acts as the scattering-free radioactive source for the experiment. Because of the high magnetic field of a Penning trap, half of the recoil ions are focussed towards the spectrometer where their energy can be probed (see next section).

The basics of Penning traps and their implementation in the WITCH setup are discussed in appendix B. Good understanding of how ions behave in the WITCH traps is essential for the data analysis. Properties of the cloud, like the spatial and energy distribution of the trapped ions, have to be known accurately since they can modify the recoil spectrum significantly. A systematic study of ion behaviour in traps using simulations was started [Coeck et al., 2007b] and is still ongoing [Van Gorp et al., 2011, Van Gorp, 2011]. Examples of how the traps were optimised in the past years are given in section 4.2.4.

A final important point for the discussion of the efficiency of the setup is the amount of ions that can be trapped in the decay trap. Trapped ions have their own Coulomb potential, and for an ion cloud containing several 10^5 ions this potential can become appreciable. In section 6.1.1 and figure 6.1 an example of the Coulomb potential generated by one million ions is given; in the centre of the cloud this potential can be 0.5 V. To trap all the ions in the cloud without losses the depth of the Penning trap needs to be higher than 0.5 V. The wish to have many ions in the trap is thus opposed to the requirement of having a low trap depth to reduce systematic effects. A good compromise between these two requirement defines a maximum number of ions that can be trapped in the decay trap; this is called the space charge limit. This limit is 10^6 – 10^7 ions at WITCH. At the moment it is considered to be closer to the lower limit (i.e. 10^6 ions), but the use of different trapping potentials and further characterisation of the traps might allow an increased amount of ions in the decay trap with an equally good understanding of systematic effects related to the trapping potential.

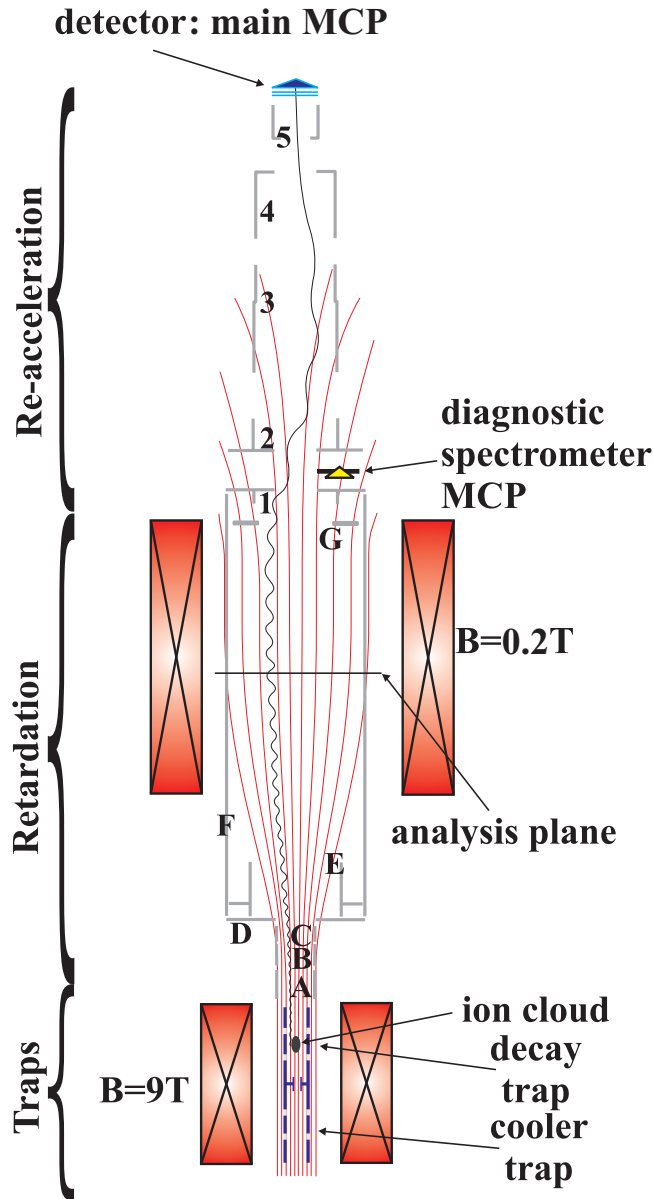


Figure 2.4 – Schematic overview of the Penning traps, the spectrometer and the detector. Ions are coming in from the bottom. The path of a possible recoil from the decay trap is indicated by a curly black line; the magnetic field lines are indicated in red dotted lines. Electrodes indicated by A-G indicate SPRETA01 to SPRETA07 respectively; they are the retardation electrodes of the spectrometer, SPRETA06 being the main retardation electrode. 1-5 refers to the following electrodes in the re-acceleration section; 1. SPACCE01, 2. SPACCE02, 3. SPEINZ01, 4. SPDRIF01 and 5. SPDRIF02.

2.4 Spectrometer

With the ions in the decay trap serving as a radioactive source, the final step in the experimental cycle is the measurement of an energy spectrum of the recoil daughter ions produced by β decay in the decay trap. Recoil endpoint energies can range from almost 0 eV up to a few keV. For ions in this energy range it is not possible to measure the energy with an energy-sensitive detector (e.g. a solid-state detector has a dead layer which the ions first need to penetrate; to realise this they typically need a kinetic of about 10 keV). The solution to this problem is to combine a retardation spectrometer (of the MAC-E type [Picard et al., 1992]) with a re-acceleration section and a detector (which is explained in the next section).

There are two important components in the spectrometer (Fig. 2.4). The first are 7 retardation electrodes which create a gradually increasing electric field starting right above the traps up until the analysis plane that is situated inside the main retardation electrode, SPRETA06. The second component is a magnet which provides a constant magnetic field in the analysis plane up to 0.2 T. The application of a potential U_r on the main retardation electrode will stop all ions that have a longitudinal energy lower than U_r/q where q is the charge of the ion. As said, the spectrometer can only probe the longitudinal energy, while the recoil momentum is oriented in a random direction. The gradual change of the magnetic field from the Penning trap region towards the analysis plane in the spectrometer causes a conversion of the radial energy of the ions into axial energy according to the following relation – due to conservation of angular momentum and which is an inverse magnetic mirror:

$$\frac{T_{1\perp}}{T_{2\perp}} = \frac{B_1}{B_2}, \quad (2.1)$$

with $T_{\perp}$ the longitudinal kinetic energy and B the magnetic field with the indices referring to different locations in the system. An example for the WITCH experiment would be a 6 T magnet field in the Penning trap region and a 0.1 T field in the spectrometer region yielding a 98.33 % conversion of radial energy into longitudinal energy. Behind the retardation electrodes the recoil ions are picked off the magnetic field lines by a set of re-acceleration electrodes at a high negative potential (typically about -8 kV). The re-accelerated ions are focussed with an einzel lens electrode onto the main MCP detector.

Retardation spectrometers are also used in other experiments like aSPECT [Glück et al., 2005] and KATRIN [Weinheimer et al., 2002]. The technical implementation of such a spectrometer is not straightforward as the combination of electric and magnetic fields can give rise to a number of specific technical issues which will be described in chapter 5.

2.5 Main MCP Detector and Data-Acquisition

To measure a high statistics recoil ion energy spectrum at WITCH a detector is needed which can detect single ions in the right energy range ($\mathcal{O}(\text{keV})$), with a high count rate ($\leq 1 \text{ MHz}$) and with a good timing resolution ($< 1 \mu\text{s}$). For this purpose an MCP detector was chosen. This type of detector can detect ions with an efficiency of $\sim 50\%$ and with a count rate of about 1 MHz . Also other types of particles like β 's and photons can be detected provided the necessary modifications to the detector are made. With an MCP detector it is also possible to measure the position distribution of the incident particles. Although this is not required for the measurement of a recoil ion energy spectrum, it provides invaluable insight into possible systematic effects.

The detector used for the measurements in this thesis is a DLD40 from Roentdek with an active diameter of 47 mm which has been replaced in the meantime by a DLD80 with an active diameter of 83 mm from the same company. Both detectors are described in detail in [Liénard et al., 2005]. They have an efficiency of $52.3(3)\%$ which is determined by the ratio of the channel aperture surface to the active surface. The detection efficiency also depends on the incident energy and angle. But these do not play a role at WITCH thanks to the re-acceleration of the recoil ions. Indeed, a rough estimation shows that the maximum angle θ an impinging particle can make with the normal to the detector surface is about 0.05° for a re-acceleration of 9 kV and a recoil energy of 500 eV . The position resolution that can be obtained with this detector is $110(26) \mu\text{m}$ [Liénard et al., 2005].

The data-acquisition is described in detail in Ref. [Kozlov et al., 2008]. It consists of two parallel branches. One fast branch is used for counting, and a slower branch is used for the position determination of the events and registration of the pulse-height. The latter can be used in the analysis as well, since the pulse-height distribution for ions and betas is different and allows for a position-dependent discrimination between β 's and ions. The slower branch has a relatively high dead-time and cannot be used by itself for the registration of a recoil ion energy spectrum. Systematic effects related to the use of an MCP as main detector are described in section 6.1.3.

2.6 Experimental Cycle

Many different steps are required to get a cooled radioactive ion cloud in the decay trap and thereafter measure a recoil ion energy spectrum. A schematic overview of the full timing cycle for WITCH is given in Fig. 2.5. A typical experimental cycle goes through the following steps;

- The ejection trigger from REXTRAP serves as the main trigger for the experiment. REXTRAP is itself triggered by the proton pulse of ISOLDE during a radioactive run.
- The beamgate and PDT are set to the correct timing so that the ions are

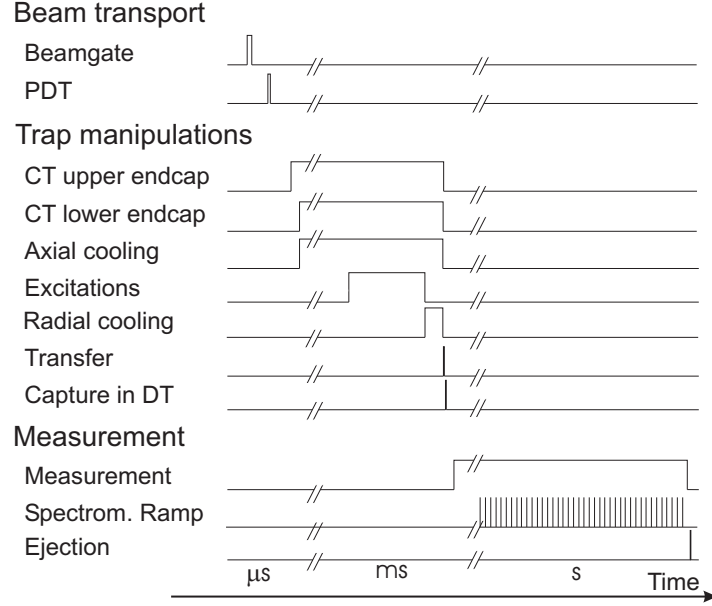


Figure 2.5 – Triggers used in a typical WITCH experimental cycle. *CT* and *DT* stand for cooler trap and decay trap respectively.

transmitted through the system and slowed down.

- The slow ions are trapped by the cooler trap. The axial energy is reduced by buffer gas collisions. Finally the ions end up in the quadrupole potential where excitations can be applied to manipulate the ion cloud.
- When the ion cloud is well prepared it is transferred into the decay trap where it is kept for the measurement. The trap cycle is described in detail in section B.2.2.
- To measure the energy of the recoil ions emerging from the decay trap, the voltage on the retardation electrodes in the spectrometer is ramped in small steps from 0 V to well above the maximum recoil energy. That way also the background can be measured and characterised. Other schemes of changing the voltages on the retardation electrodes can be used as well.
- The ions that are still present in the decay trap after the measurement are ejected towards the PDT to avoid contamination of the spectrometer and the detector.

Note that with a higher repetition rate for the PDT being possible now it is necessary to get several REXTRAP triggers during one experimental cycle (see section 4.2.1). Further, the procedure of ramping the spectrometer from 0 V to a certain higher voltage during one experimental cycle is currently used to have

a proper normalisation. If it were possible to measure the number of ions in the trap for each trap load, it would be possible to keep the voltage in the spectrometer constant during one experimental cycle. The possible implementation of such a normalisation procedure is discussed in section 4.2.3.

2.7 Control System

The experimental cycle mentioned in the previous section requires many types of different hardware working together. The optimisation of that cycle thus requires control over all of those devices. A control system based on LabVIEW has been developed to this end. It is described in detail in appendix A which consists mainly of a published article [Tandecki et al., 2011]. This control system (and earlier versions of it) has increased the beam transport efficiency, improved the operation of the traps and in general setting up of the system can be done faster and in a more systematic way.

2.8 Data-Analysis Procedure

There is no standard procedure for the analysis of WITCH data yet, but it is clear that this will have to be done with the aid of simulations. The basic idea is the same as used for nuclear orientation experiments [Wauters et al., 2009] where the β -asymmetry parameter is extracted.

The data-analysis procedure being developed by using two simulation packages. One simulation package will investigate the properties of the radioactive source (i.e. the ion cloud) in detail, while the second simulation package will calculate the trajectory of the recoil ions upon leaving the decay trap.

2.8.1 Source

For precision experiments dealing with a radioactive source, the exact properties of the source need to be known. Since the source for the WITCH experiment is contained in the decay trap, good knowledge about this source requires a detailed knowledge of the behaviour of ion clouds in Penning traps. This is not straightforward as there are no analytical solutions for the motion of $\sim 10^6$ particles in a trap; see section B.1.3. To characterise the ion cloud, simulations are therefore performed. For WITCH the code called Simbuca was developed, which can, however, also be used in other experiments [Van Gorp et al., 2011]. One of the important aims of the simulations with this code is to investigate the phase space and its (potential) evolution over time. The importance of these simulations is motivated further in chapter 6.

2.8.2 Tracking

Once the phase space distribution of the ions in the source is precisely known, the creation of recoil ions and their path through the spectrometer needs to be simulated. This is performed by a Monte Carlo simulation routine – SimWITCH [Friedag, 2008, Mader, 2010, Friedag, 2012] – that was developed for WITCH based on a routine used for the simulations of electrons in KATRIN [Glück, 2010]. Recoil ions are created with a random angle and energy. The energy of the ions is distributed according to the recoil ion energy spectrum shape expected in the Standard-Model, but it can also be simulated for non-Standard Model physics. The recoil energy is modified by the initial velocity of the decay mother ions, i.e. thermal Doppler broadening, and by the effect of possible de-excitation of the daughter ion, e.g. due to γ decay in flight.

Once the ions are created the tracking through the spectrometer can be started. For this a detailed description of the potentials is included into the simulations. Other effects – like scattering on rest gas – can also be taken into account. To fit a recoil ion spectrum several simulations with high statistics and with different conditions are required. These include different charge states of the daughter ion, different excited energy states in the daughter, different retardation potentials – in a single simulation only static voltages can be used –, different β - ν angular correlation coefficients, etc. For each simulation a large amount of statistics is required so that the simulations do not limit the statistical uncertainty. Each simulation will generate a specific recoil ion energy spectrum which has to be combined with the spectra from the other simulations to fit the measured spectrum.

Once a reasonable fit of a measured spectrum is obtained – and thus a value for the β - ν angular correlation coefficient with a corresponding statistical uncertainty –, the systematic uncertainty on the resulting value for a has to be estimated. All possible – and currently thought of – systematic effects are listed in chapter 6. In principle one has to repeat all simulations from the previous paragraph but in slightly different conditions. For example one has to look what the effect on the final result is if the shape of the ion cloud or the energy distribution is slightly altered. From this one can then deduce a systematic uncertainty. Even though performing the initial simulations for an extraction of a might seem cumbersome, a detailed estimation of the systematic uncertainties presently requires more time.

2.9 Choice of Isotopes

The choice of the radioactive isotope for this type of experiments is always a compromise between what is interesting from a physics point of view and the technical limits imposed by the experiment. Luckily the ISOLDE facility offers a broad range of isotopes.

- The **half-life** should be on the order of one second. A too short half-life will not leave enough time to prepare the ion cloud. Typically an

accumulation time of 100 ms is used in REXTRAP while in the WITCH cooler trap about one second is needed to obtain a well-cooled ion cloud. With a half-life shorter than 500 ms more than 75 % of the created ions will have decayed before they reach the decay trap. A too long half-life will increase the time needed to obtain a sufficient amount of statistics. The optimal half-life for WITCH is $\mathcal{O}(1\text{ s})$ [Delauré, 2004].

- The **recoil energy** of the ions should be in the range of 100 to 500 eV. The upper limit is set by the voltage that can be applied to the retardation electrodes of the spectrometer taking into account that some part above the maximum recoil energy is also needed for characterisation of the background.
- Measurements with ions that have a **low ionisation potential** are preferable. This avoids loss of ions by charge exchange which can occur both in WITCH and REXTRAP. It has been shown (with ^{35}Ar) that this is not really a limitation of the WITCH setup anymore after the recent vacuum upgrade (see section 4.1.5). Nonetheless it still needs to be taken into account when working with REXTRAP.
- Because of the high statistics needed for a successful measurement also the **production yield** needs to be high enough. The maximum trap load of the decay trap is of the order of 10^6 ions. Taking into account a full transmission efficiency of 10 % this translates into a trap load of 10^7 ions in REXTRAP which is the limit for that setup.
- Related to the previous item is the issue of **isobaric or isomeric contamination**. Stable contaminations will, to first approximation, not disturb the measurement of the recoil ion energy spectrum, but it will fill the trap and thus reduce the number of radioactive ions in the trap. A contamination with the same yield as the isotope of interest will cause an increase of $\sqrt{2}$ of the statistical uncertainty.
- The **decay mode** is also an important factor. A 1^+ ion decaying via β^- decay will become a 2^+ ion, while the same 1^+ ion decaying via β^+ decay will become a neutral atom. With this information it would seem impossible to measure the energy of recoils from β^+ decay as they would not be retarded in the spectrometer. Luckily it is possible that some electrons are shaken off because of the sudden change of charge in the nucleus that occurs in a decay. As a general rule of thumb about 10 % of the daughter ions from β^+ decay will emerge as 1^+ ions. A measurement of the recoil ion energy from β^+ decay will thus contain typically about 10 times less statistics than the same measurement (same yield, half-life, etc.) with a β^- decaying isotope.

These are the practical limitations one has to think of before starting a measurement. Besides these constraints also the properties of the isotopes themselves can render the analysis of the recoil spectrum more difficult. It has to be noted that in general only the higher energy part of the energy spectrum will be useful

as the lower part contains events from all higher charge states of the daughter ion. The charge state distributions are not known precisely enough to include this in the analysis; a dedicated measurement will have to be performed.

- A **stable daughter isotope** is desirable. If the daughter isotope is not stable and the half-life is rather long (order of days or longer) it will not interfere with the measurement too much. If it is rather short, non-decayed daughter isotopes will be implanted on the MCP detector and decay there, thus causing significant background in the recoil ion energy spectrum. For very short half-lives (order of milliseconds or shorter) decays from the daughter in-flight will distort the measured recoil ion energy spectrum. One could take this into account when performing the simulations for the data-analysis, but this would increase the time required for the simulations significantly and increase the uncertainty of the final result.
- **Radioactive isobaric and isomeric contaminations** will interfere with a measurement on the isotope of interest. This can be avoided if the maximum endpoint energy of these is located in the lower half of the spectrum. In that case it will merely interfere with the measurement by reducing the yield of the useful isotope.
- In general the full **decay scheme** of the isotope under investigation is important. Usually the daughter isotope will not be in its ground state right after the decay. It will be in an excited state and will proceed to the ground state by the emission of γ 's or ejection of electrons. This has two consequences; first of all the recoil energy will be lower when the daughter is in an excited state and secondly the particles that de-excite the daughter isotope will give an additional recoil kick to the daughter. These two factors will again distort the recoil spectrum. This is not a major problem if the decay scheme is precisely known, but it has to be taken into account during the analysis.

With all the previous limitations in mind one still has to choose an interesting candidate for a measurement from a physics point of view. Currently one can distinguish between three types of interesting isotopes at WITCH; one that will enable the investigation of scalar currents, a second one that will provide mono-energetic decays for calibration purposes and a third one that will allow to test the system with high statistics and in all its aspects. The most important ones are of course those that will allow reaching the physics goal set out for the experiment. In this respect $0^+ \rightarrow 0^+$ superallowed transitions are very interesting because they are pure Fermi decays and have the right half-life for a measurement [Hardy & Towner, 2005]. Another category of interesting isotopes are the so-called mirror transitions in which the amount of protons and neutrons is mirrored in mother and daughter nucleus. They are mixed transitions, but some mirror nuclei decay primarily via a Fermi-type decay [Severijns et al., 2008]. Interesting isotopes from a physical point of view and with the right half-life are given in table 2.3.

It is hard to find isotopes with a high fraction of electron capture decays and a short enough half-life. Electron capture decays are favoured in isotope decaying with a low Q -value; in general lower Q -values lead to longer half-lives. Interesting electron capture decaying isotopes are listed in table 2.4.

Other isotopes that are interesting for a test measurement are isotopes that meet the listed requirements but of which the extraction of physics is not easy. This can be the case, for instance, if the mixing ratio is not precisely known or the decay scheme is rather complex. Such an isotope, ^{124}In , has been used in the past, but other isotopes can be considered as well (e.g. ^{114}Ag).

mother	state	$t_{1/2}$ (s)	yield (ions/ μC)	daughter	state	$t_{1/2}$ (s)	ΔE (MeV)	$T_{R,max}$ (eV)	P_{EC} %	BR %	a_{SM}
^{26}Al	isom	6.345	$6.8 \cdot 10^4$	^{26}Mg	gs	stable	4.23255(17)	280.7	0.082	> 99.997	1
	gs	$7.4 \cdot 10^5\text{y}$	*		exc	476 fs	2.20	53.2		97.3	
^{34}Cl	gs	1.527	$1.3 \cdot 10^3$	^{34}S	gs	stable	5.49178(20)	387.9	0.080	> 99.988	1
	isom	1920	$2.2 \cdot 10^5$		exc	325 fs	3.511	138		28.5	
^{38}K	isom	0.924	$6.3 \cdot 10^6$	^{38}Ar	gs	stable	6.04440(11)	429.1	0.085	> 99.998	1
	gs	458	$7.9 \cdot 10^7$		exc	470 fs	3.7456	144.2		99.8	
^{42}Sc	gs	0.681	*	^{42}Ca	gs	stable	5.9131	408.9		< 0.6	1
	excit	61.7	$1.5 \cdot 10^3$		exc	250 fs	6.42563(38)	444.2	0.099	99.9941(14)	
^{46}V	gs	0.423	0	^{46}Ti	gs	stable	3.8528	139.5		100	1
^{50}Mn	gs	0.283	$7.6 \cdot 10^5$	^{50}Cr	gs	$1.8 \cdot 10^{17}\text{y}$	7.05071(89)	496.6	0.101	$99.9848^{+0.0013}_{-0.0042}$	1
	isom	105	*		exc	1.25 ps	7.63243(23)	542.3	0.107	99.9423(30)	
^{33}Cl	gs	2.5111	$1.4 \cdot 10^2$	^{33}S	gs	stable	4.6983	185.6		8.0	0.8848
^{35}Ar	gs	1.7752	$4.3 \cdot 10^7$	^{35}Cl	exc	1.17 ps	5.5826(4)	414.5	0.074	98.45(14)	0.9004
					exc	150 fs	4.742	287.1		0.48	
							5.9661(7)	452.6	0.072	98.36(7)	
							4.7458	271.3		1.23	

Table 2.3 – Table of interesting isotopes for a β - ν -angular correlation measurement with the WITCH experiment as listed in Ref. [Coeck, 2007]. Only $0^+ \rightarrow 0^+$ superallowed transitions [Hardy & Towner, 2005] and mirror nuclei [Severijns et al., 2008] that have a large Fermi contribution in their β decay ($|\rho|^2 < 0.1$) and with $0.2\text{s} < t_{1/2} < 10\text{s}$ are included.
*No information available.

mother	state	$t_{1/2}$ (s)	yield (ions/ μC)	daughter	state	$t_{1/2-}$ (s)	ΔE (MeV)	$T_{R,max}$ (eV)	$T_{R,EC}$ (eV)	P_{EC} %	BR %
^{144}Eu	gs	10.2(1)	$1.5 \cdot 10^6$	^{144}Sm	gs	stable	5.293(17)	126.2	150.4	9.68(19)	79.7(6)
					exc	84.4(25) fs	3.633(17)	64	82		5.9(4)
					exc	47 fs	2.870(17)	43	57		0.58(5)
^{140}Pm			*	^{140}Nd	exc	> 1.2 ps	2.815(17)	41	56		0.87(7)
	gs	9.2(2)			gs	3.37(2) days	6.045(24)	116.5	140.2	9.90(24)	83.6(6)
	isom	357(30)									

Table 2.4 – List of potential electron capture decaying isotopes for use in WITCH. Based on Ref. [Coeck, 2007, NND, 2011].

Chapter 3

Overview of Radioactive WITCH Runs

In this chapter an overview is given of the radioactive runs that were performed in the course of this work. A first successful recoil ion energy spectrum was measured in the decay of ^{124}In , two runs on ^{35}Ar were performed and the measurement of a electron capture decay was attempted. This chronological overview provides the right context for chapters 4 and 5, which discuss a number of items in greater detail and this is not chronologically but rather thematically. In the former the most important upgrades in the past years are described. In the latter an issue which has been present in the spectrometer is described.

3.1 2006: ^{124}In

A first successful radioactive run was carried out in November 2006. The recoil energy spectrum from the decay of ^{124}In was measured. These data were analysed on two separate occasions (see [Coeck, 2007] and [Vermeeren, 2010]). Since there were still too many unknown parameters, like e.g.

- the ratio of ^{124}In to $^{124\text{m}}\text{In}$,
- the spin assignments of different levels in the decay schemes,
- the charge state distribution of the recoil ions, and
- the ion could (source) properties,

it was not possible to deduce even a rough value for the β - ν correlation parameter in ^{124}In decay. Rather, the β - ν correlation parameter was used as input for the various simulations performed and the charge state distribution of the daughter ions was extracted. $^{124}\text{In}^{1+}$ ions decay into $^{124}\text{Sn}^{2+}$ ions, but more electrons can be emitted caused by two effects [Carlson et al., 1963, Carlson, 1975]

- Electron shake-off is triggered by the sudden change of the nuclear charge. Due to the difference in electron wave function before and after the decay, there is a chance that the electron will be ejected. Similar arguments are true for the sudden change of the momentum of the atom or ion, but this only needs to be taken into account for lighter nuclei (e.g. ${}^6\text{He}$). The charge state distribution resulting from this can be modelled by an exponential function; i.e. the probability for higher charge states decreases exponentially.
- Electrons can also be emitted from the atom or ion by Auger cascades following vacancies in the electron shells. These vacancies can be created by electron capture where an electron from the inner electron shells participates in the decay – which is not the case for ${}^{124}\text{In}$ –, or by internal conversion where instead of de-exciting via γ emission the nucleus de-excites by transferring energy to an electron. After an initial vacancy more electrons can be emitted in the following Auger processes. The charge state distribution resulting from this effect depends on the atomic structure of the element. If the atom or ion has e.g. 5 loosely-bound electrons, the resulting charge state distribution will be a bell-shaped function centred around the 5^+ charge state.

In both analyses, the shake-off effect is modelled according to experimental data from [Snell & Pleasonton, 1958] for ${}^{133}\text{Xe}$ decay, modified such that 2^+ is the dominant charge state. The Auger cascades effect is modelled with a Gaussian distribution. This leads to three fit parameters for the charge state distribution; the ratio between the amplitudes of the exponential (shake-off) and gaussian (Auger) distribution, and the centre and width of the Gaussian distribution. In the analyses the following fit parameters were then used;

- three parameters for the charge state distribution, as mentioned before,
- an offset on the retardation potential; this can be caused by the electronics, but also by the contact potential difference (see section 6.3.2). This was not used in [Vermeeren, 2010],
- the fraction of ${}^{124}\text{In}$ to ${}^{124\text{m}}\text{In}$,
- a scaling factor for the β -background,
- an overall scaling for the total amount of recoil ions that reached the MCP detector.

The spectrum depends heavily on the charge state; the endpoint energy of 195.6 eV for ${}^{124}\text{Sn}$ ions after the decay of ${}^{124}\text{In}$ will be registered at a retardation voltage of $195.6/q$ V for recoil ions with a charge q . The resulting spectra are shown in Fig. 3.1. Both panels show the experimental data plus simulations. The extraction of the charge state distribution did not succeed, as the discrepancy between [Coeck, 2007] and [Vermeeren, 2010] shows (see Fig. 3.2). The systematic uncertainties in the measurement were not characterised sufficiently

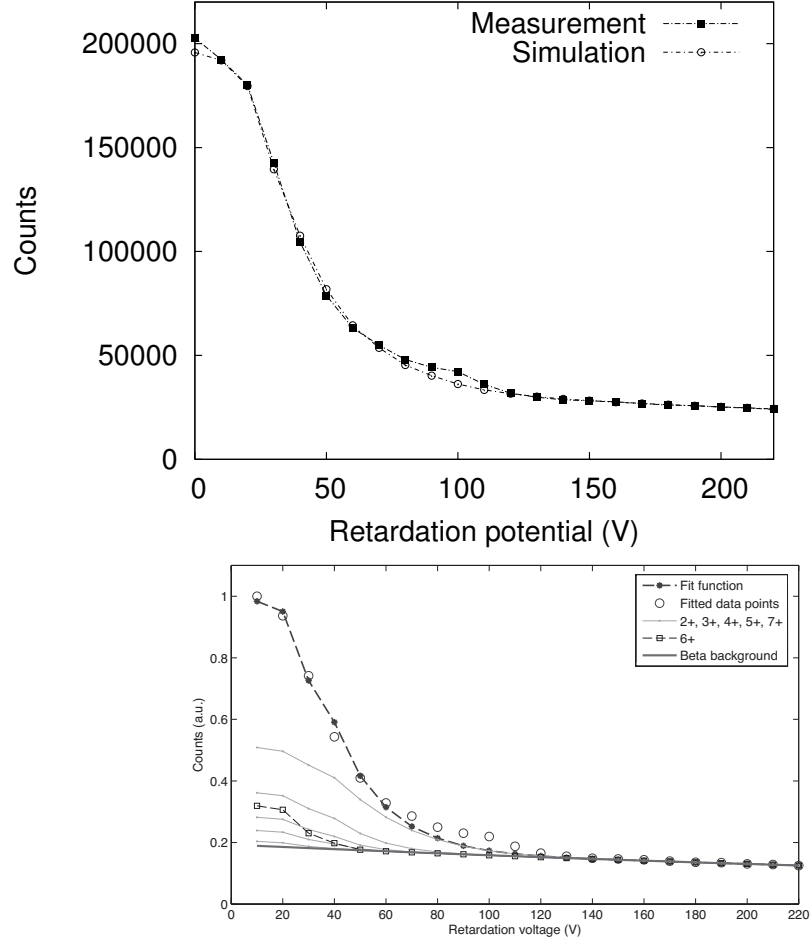


Figure 3.1 – Fitted retardation spectrum obtained from the decay of ^{124}In (which has an endpoint of 195.6 eV). The **top** panel is from [Coeck, 2007] and the **bottom** panel from [Vermeeren, 2010]. The experimental data for both panels is the same. The recoil ion energy spectrum is plotted as a function of the retardation voltage/potential, but originally it was recorded in function of time with a one-to-one correspondence to a certain retardation voltage. Above ~ 125 V one can see the β -background which is exponentially decreasing. In the bottom panel this β -background is also explicitly plotted. The bottom panel also shows the different simulated spectra for different charge states (for the 2^+ , 3^+ , 4^+ , 5^+ and 7^+ charge states, the contribution in the fitted spectrum is inversely proportional to the charge state); the spectrum for the 6^+ charge state is plotted separately as it is the dominant charge state from that analysis. These different components (different charge states plus β -background) add up to the ‘Fit function’.

well as can be seen from the poor fit of the data (see figure 3.1). In the first analysis the contribution of internal conversion in the charge state distribution has its maximum at 4^+ , while in the latter analysis this is situated at 6^+ . The dominant charge state of 4^+ can be explained by the atomic structure of ^{124}Sn : $[\text{Kr}] 5s^2 4d^{10} 5p^2$, with the $5s$ and $5p$ electrons having the lowest binding energy. For the obtained 6^+ dominant charge state in the other analysis there is no apparent real physical explanation. However, the fact that the contribution of the internal conversion to the charge state distribution is only a single charge state, has not been observed in measurements before.

The two analyses were performed using different assumptions and different simulation routines. In the first analysis SimION [sim, 2010] was used, while in the second one SimWITCH [Friedag, 2008, Mader, 2010] was utilised. One of the major uncertainties that were hampering a proper analysis of the data, are the exact properties of the ion cloud. A voltage of 8.5 V was needed on the endcap electrodes in the decay trap to trap the ions, so in the first analysis an energy (temperature) of $\sim 8.5 \text{ eV}$ (100000 K) was used as the mean energy (temperature) of the ions obeying a Maxwell-Boltzmann energy distribution. In the second analysis a more narrow energy distribution was assumed (i.e. a Gaussian distribution with a mean of 8.5 eV and a standard deviation of 1.5 eV). The latter assumption was based on later measurements that showed that the voltage on the endcap electrodes is not a good measure for the energy distribution of the ions. A well-cooled ion cloud can gain extra energy during the transfer from the cooler trap to the decay trap; this does not necessarily broaden the energy distribution, but it can merely give an energy offset. Another difference between the two analyses is that an offset on the retardation potential was not used in the second analysis.

Other features of the spectrum which are not fully understood are the ‘bump’ at 100 V and the exact shape of the spectrum close to 0 V. The second analysis was motivated by understanding this bump at 100 V better. Originally it was thought to be an experimental artifact, however, it can also be explained by assuming a lower energy for the ion cloud and then this bump can be the end-point of the recoil ion energy spectrum. Unfortunately, a better understanding of this feature was not obtained, as the correct energy distribution for the ion cloud was not measured at the time. The exact shape of the lowest-energy part of the spectrum might also interfere with the extraction of the charge state distribution. The shape in the lowest-energy part is easily influenced by high charge states; this can easily lead to a wrong extraction of the charge state distribution. Moreover, an offset of the retardation potential will influence the analysis significantly. The latter is probably the main reason for the discrepancy between the two analyses.

Other results from this run have been published in Ref. [Beck et al., 2011], which is also attached in appendix D. In that paper it is not attempted to extract a charge state distribution for ^{124}Sn after the decay. Rather, solid arguments are given to show that the measured spectrum was indeed a recoil ion energy spectrum. This was not clear when the measurements were actually performed with a source of secondary ionisation somewhere in the system; the measurement

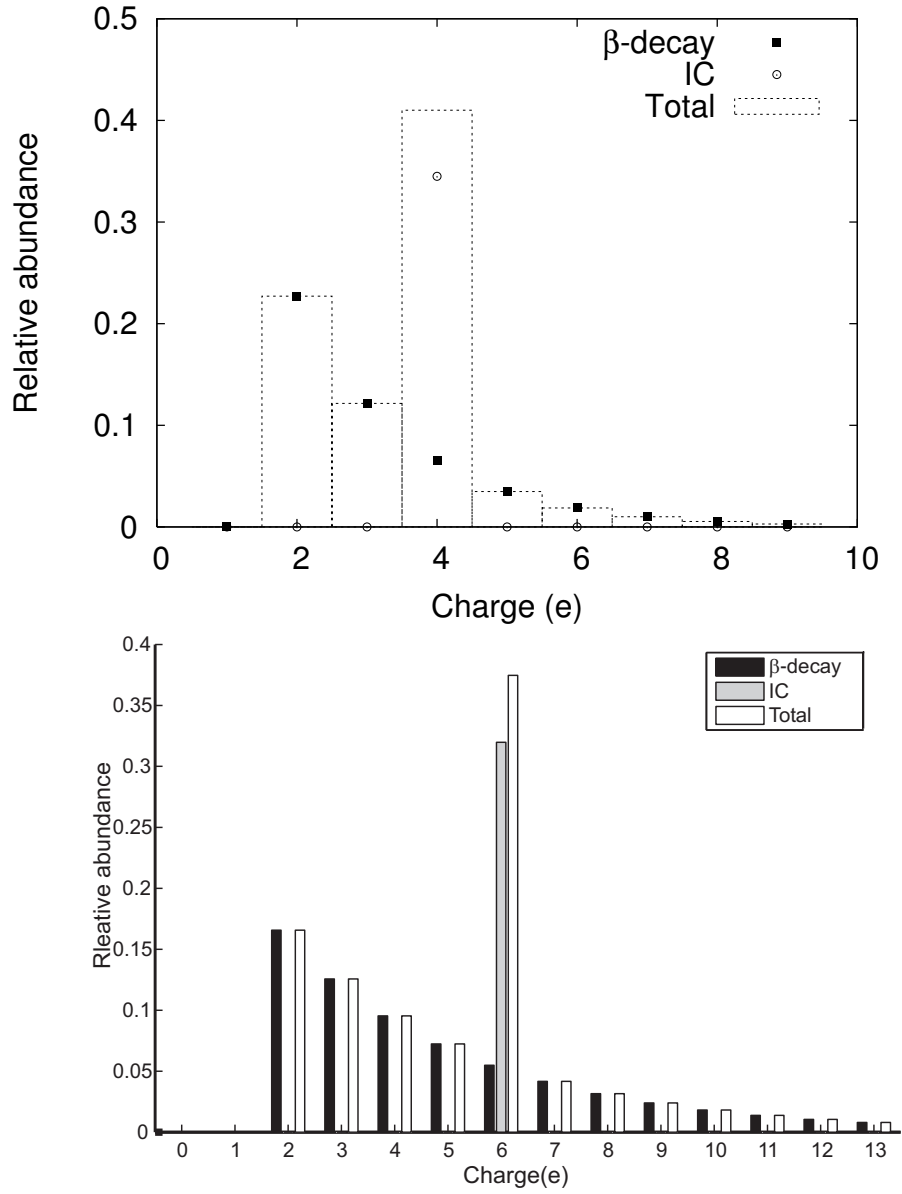


Figure 3.2 – Charge state distribution obtained in Ref. [Coeck, 2007] (top) and Ref. [Vermeeren, 2010] (bottom). Both graphs show the contribution in the charge state distribution of electron shake-off (i.e. indicated by ' β -decay') and of internal conversion plus the following Auger processes (i.e. 'IC').

of the recoil ion energy spectrum was done with the einzel lens electrode in the re-acceleration section serving as retardation electrode. Using the retardation spectrometer – as should be the case for a normal operation of the system – caused the recoil ion energy spectrum to be disturbed by ionisation effects and discharges (see chapter 5). In the paper, also properties of the ion cloud are investigated, based on measurements and simulations. The main results discussed in the paper are;

- An upper limit for losses in the decay trap; i.e. less than 2.6 % per second at a confidence level of 99.5 %,
- The average trap load is estimated to be $1.4(2) \cdot 10^5$ ions for that experiment.
- The radius of the ion cloud is estimated to lie between 1.7 mm and 4.3 mm, which is larger than the radius of the differential pumping diaphragm between the cooler and decay trap,
- The signal to noise ratio in the obtained recoil ion energy spectrum is $S/N = 4.06 \pm 0.23$,
- The spot of the recoil ions on the detector has its centre at 2.2 ± 0.1 mm away from the centre of the detector. This corresponds to an angle of $0.047(2)^\circ$, when taking into account a distance of 2.644 m between the detector and the centre of the decay trap.

3.2 2007: ^{35}Ar

The ^{35}Ar run was complicated by several issues that will be discussed in the next section. However, an interesting result is presented; i.e. the half-life of the radioactive ions shot onto the main detection MCP (see Fig. 3.3). This technique is often used at the start of a radioactive run to check whether the half-life matches with the literature value. This was, however, not the case here, i.e. the half-life is falling short; it was 1.38(8) s which is too far from the expected 1.7752(10) s [Severijns et al., 2008] to be attributed to statistical fluctuations. This effect was not observed in the past when measured with a diagnostic MCP detector [Kozlov, 2005, p. 128–130]. However, it was seen again during the ^{35}Ar run of 2009; in section 3.4.1 possible effects leading to this deviating value for the half-life will be discussed.

3.2.1 Discussion

Three important issues were identified during the ^{35}Ar run of 2007;

- The purity of the beam was a major issue during the run. The yield of the stable isobaric contamination ^{35}Cl was much higher than the yield of ^{35}Ar . Without optimisation it was 200 times more abundant. With some

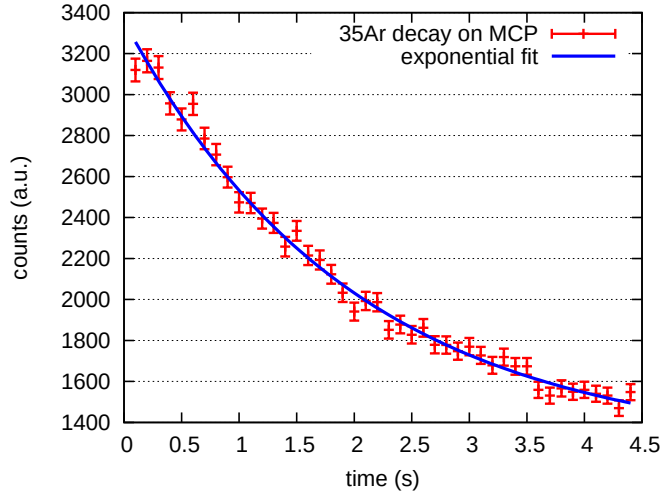


Figure 3.3 – Decay of ^{35}Ar as observed during the run in 2007, by implanting a beam on the main detection MCP with a kinetic energy of ~ 37 keV – i.e. the ISOLDE beam energy plus the acceleration caused by the MCP front plate voltage. The fit yielded the following values; 1.38(8) s for the half-life, 1270(40) for the background, 2090(30) for the amplitude, with a reduced χ^2 of 1.066. The high background can be caused by ionisation effects or a not sufficiently well tuned detector and data-acquisition.

optimisation (like a better tune and proper gating) the ratio of ^{35}Cl to ^{35}Ar was reduced to 25 to 1. The problem with this is not the contamination itself, because this will not be detected in a recoil ion energy measurement, but the fact that this isobaric contamination leads to a reduction of the number of useful ^{35}Ar ions that can be stored in the traps. Penning traps have a limited amount of ions they can store due to space charge effects; the maximum load of REXTRAP is of the order of 10^7 ions. If REXTRAP is fully loaded with that $^{35}\text{Cl}/^{35}\text{Ar}$ beam coming from ISOLDE there would only be $4 \cdot 10^5$ ^{35}Ar ions present in the trap.

- Neutralisation of the argon ions due to charge exchange ($^{35}\text{Ar}^+ + \text{X} \rightarrow ^{35}\text{Ar} + \text{X}^+$) was non-negligible both in REXTRAP and WITCH (see Fig. 3.4). In REXTRAP about half of the argon ions were lost in 70 ms. This prevented the accumulation of a sufficient amount of argon ions. If the $4 \cdot 10^5$ ions from above are used, and we assume an accumulation time of 100 ms, then only $\sim 1 \cdot 10^4$ argon ions enter the WITCH setup. Though this is far from ideal the problem in the WITCH cooler trap was even more problematic; there half of the ^{35}Ar ions were lost after only 8 ms due to rest gas impurities or impurities in the buffer gas. This rapid loss of ^{35}Ar ions prevented a proper preparation of the ion cloud. For the rest of the measurement the cooler trap was therefore bypassed and the ions were injected directly into the decay trap.

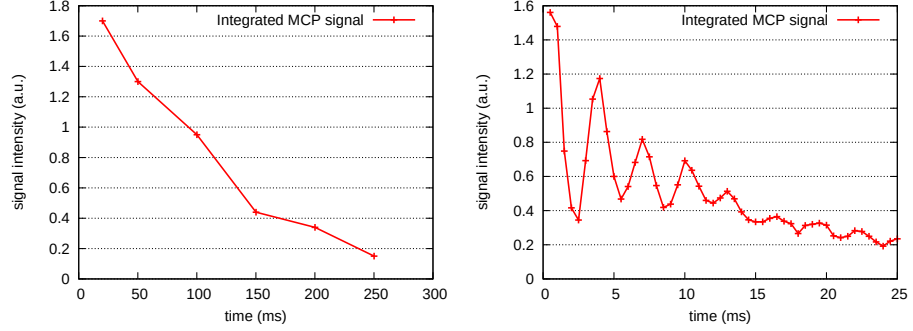


Figure 3.4 – The amount of ^{35}Ar ions leaving REXTRAP (**left**) and WITCH (**right**) after a specified amount of time. The oscillations in the measurement at WITCH are an experimental artifact caused by simultaneously lowering the voltages on both endcap electrodes of the cooler trap; if the ion cloud has an average momentum pointing towards the cooler trap they will go upstream through the pumping diaphragm and not be detected.

- With the non-cooled ion cloud in the decay trap some measurements could still be performed (e.g. checking the count rate on the main MCP detector as a function of different voltages on the retardation electrodes or as a function of the voltage applied to the endcaps of the decay trap). The issue of the secondary ionisation observed during the ^{124}In run one year before turned out to be still present, be it in a somewhat different form (see chapter 5).

Thorough discussions after the run and a first look at the acquired data led to the formulation of several solutions for each issue;

- The high yield of ^{35}Cl was an issue to be solved by the target group of ISOLDE. It turned out that the ^{35}Cl was not created by proton impact, but rather it was an artifact from the target's ion source. Chlorine is often a component in cleaning agents, and such a cleaning agent had apparently also been applied to the target used in this run. When heating the ion source and the target, the chlorine is then released along with the argon.
- To avoid charge exchange in the WITCH cooler trap a general improvement of the vacuum and more specifically of the vacuum in the buffer gas system were proposed. It was observed that the rate of the charge exchange was inversely proportional to the buffer gas pressure, meaning that impurities in the buffer gas system were the main cause of the charge exchange. The details of this are given in section 4.1.1 and 4.1.2. The general idea was to remove atoms or molecules with a low ionisation energy from the rest gas and also to reduce the rest gas pressure as much as possible. A reduction of one order of magnitude was aimed at; from

10^{-8} mbar to 10^{-9} mbar, since at this rest gas pressure, the contaminating ions in the rest gas and the helium buffer gas are at the same level. For more details, see section 4.1.3.

- The solution for avoiding the creation of secondary ionisation was not so clear. Several improvements were proposed which would then be implemented all together and afterwards tested again. These included a general improvement of the vacuum to reduce the ionisation of the rest gas and electropolishing of important electrodes to lower possible electron field emission. Since the mechanism of this secondary ionisation was not clearly understood yet, it was not clear whether these improvements would prove to be adequate.

The extensive plan of improvements started a period of almost two years where the system was taken apart, parts were exchanged or treated and where everything had to be recommissioned finally. Details on the technical improvements that were implemented in this period can be found in chapter 4.

3.3 2009: ^{124}In

The ^{124}In run in July 2009 was the first after a long period of upgrades; it served as a test measurement after all the changes that had been made to the system. This run was marked by issues on both the WITCH and ISOLDE side. Since this was the first time in about two years that the beam from REXTRAP to WITCH had to be set up, the tune was less than optimal and did not yield the transmission efficiency of 10–20 % obtained in previous runs; it was of the order of 1 %.

For data-taking this was not a very successful run. However, for the general operation of the setup and the identification of some remaining technical shortcomings this run was extremely valuable (e.g. some of the electronics of the PDT had to be improved). It paved the road for a smoother ^{35}Ar run at the end of that year.

3.4 2009: ^{35}Ar

The ^{35}Ar run in 2009 was a test case to see if all the upgrades done since the ^{35}Ar run in 2007 would function properly, some of them being specifically related to running with argon. In principle all of the encountered issues were taken care of, but the final test is always a radioactive run as some effects (like the secondary ionisation) cannot be characterised by offline measurements. In that respect the run was successful; the ^{35}Ar to ^{35}Cl ratio was now about 5 to 1 and the charge exchange (i.e. neutralisation) problem in the WITCH cooler trap was solved. Also the huge discharges caused by secondary ionisation had disappeared. However, another much weaker type of secondary ionisation which did not manifest itself as discharges like in the previous years, but rather

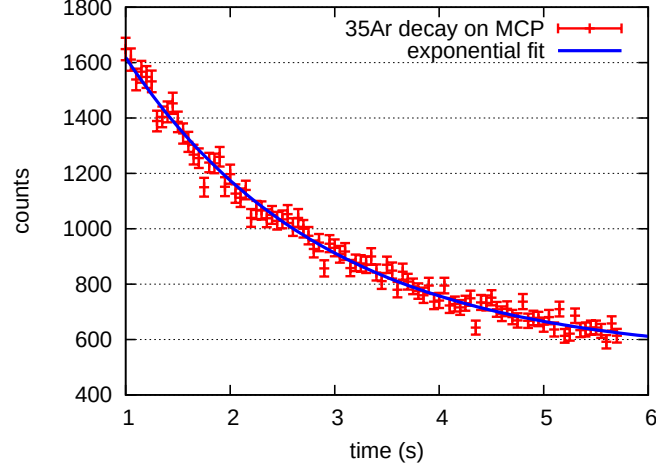


Figure 3.5 – Half-life of ^{35}Ar run in 2009, by implanting on the main detection MCP. The reduced χ^2 of the fit is 1.15. The fitted half-life is 1.31(6) s.

as an increased count rate, was discovered. Due to this unexpected phenomenon which prevented good quality data-taking, the run was not a complete success.

3.4.1 ^{35}Ar Half-life Measurement

A measurement of the radioactive decay when shooting the ions from the decay trap onto the main detection MCP yielded a fitted half-life of 1.31(6) s; in this case the implantation energy is determined by the high negative potential of the detection surface (i.e. ~ 6 keV) towards which the ions are accelerated. The cause of the deviation from the actual ^{35}Ar half-life is not clear, but it was already observed in the ^{35}Ar run of 2007. There are a few possibilities;

1. Part of the argon could have diffused out of the detector during the measurement, as the implantation energy was only of the order of 6 keV. During the 2007 run the implantation energy was 37 keV.
2. Radioactive contamination might have been present in the system. The only possibility is $^{70}\text{Kr}^{2+}$ with a half-life of 59 ms. It could be transmitted from the ISOLDE target to the WITCH detection system since it has the same mass over charge ratio as $^{35}\text{Ar}^{1+}$. However, in view of its short half-life, it seems rather unlikely that a strong component of ^{70}Kr would have been present.
3. Detector effects can change the measured half-life due to saturation and/or dead time of the detector or data-acquisition. Saturation due to the impact of the ions would decrease the amount of detected ions in the first bins and

Table 3.1 – Summary of the measured half-lives during WITCH measurements.

Isotope	Year	Detector	Implantation Energy (keV)	Exp. $t_{1/2}$ (s)	Lit. $t_{1/2}$ (s)
^{35}Ar	2004	diagnostic	32	1.70(5)	1.7752(10)
^{124}In	2006	main	37	3.73(8)	3.11(10)
$^{124\text{m}}\text{In}$					3.7(2)
^{35}Ar	2007	main	37	1.38(8)	1.7752(10)
^{35}Ar	2009	main	6	1.31(6)	1.7752(10)

thus increase the half-life (see e.g. [Coeck et al., 2006, Beck et al., 2011]). The same is true for dead time effects. High count rates are most influenced by this; i.e. in this case again the first bins and this would increase the half-life as well. None of these effects can explain the half-life that is lower than the adopted value.

To come up with a plausible explanation for the decreased half-life, four data sets are available (see Tab. 3.1). The fact that during the ^{124}In run in 2006 an acceptable value (i.e. 3.73(8) s [Beck et al., 2011]) for the half-life was observed, initially led to the tentative conclusion of argon diffusion out of the detector during the measurement. However, during a (short) run with ^{35}Ar in 2004 the half-life was measured on a diagnostic MCP detector downstream of the 90° bender; that measured half-life (i.e. 1.70(5) s [Kozlov, 2005]) is consistent with the literature value. Diffusion of ^{35}Ar out of the detector is still the most likely explanation for the observed half-lives. During the beam time of 2009 the ^{35}Ar half-life was shorter than the one measured in 2007. This can be explained by a lower implantation depth. The alloy used for the coating of the DLD-40 from RoentDek is nichrome; the implantation depth for ^{35}Ar with an energy of ~ 37 keV is 16.2 nm and for 6 keV it is 3.8 nm – calculated with SRIM [SRI, 2011]. The diagnostic MCPs (from Delmar Ventures) either use a Inconel, nichrome, or chromium coating; they all yield an implantation depth of 14–17 nm. The origin of the discrepancy of the data from 2004 and 2007/2009 could then possibly be explained by a different crystal or amorphous structure of the MCP coating in the two different detectors. Also, vacuum plays a role in diffusion processes. The vacuum during the 2004 run is not known.

3.4.2 ^{35}Ar Retardation Spectrum

The theoretical energy spectrum for recoils from ^{35}Ar decay is shown in Fig. 1.2, where for ^{35}Ar the shape is closest to the curve shown for $a = 1$. Contributions from higher charge states (than 1^+) should be around 10%. The recoil ion endpoint energy is 453 eV. Also, almost no γ radiation is emitted during the decay of ^{35}Ar (the branching ratio for decay to the ground state of ^{35}Cl is 98.02(3) %), except for the 511 keV γ 's due to β^+ annihilation which do not change the shape of the recoil ion energy spectrum. For the decay scheme of ^{35}Ar , see figure E.1. A recoil energy spectrum is measured by obtaining the

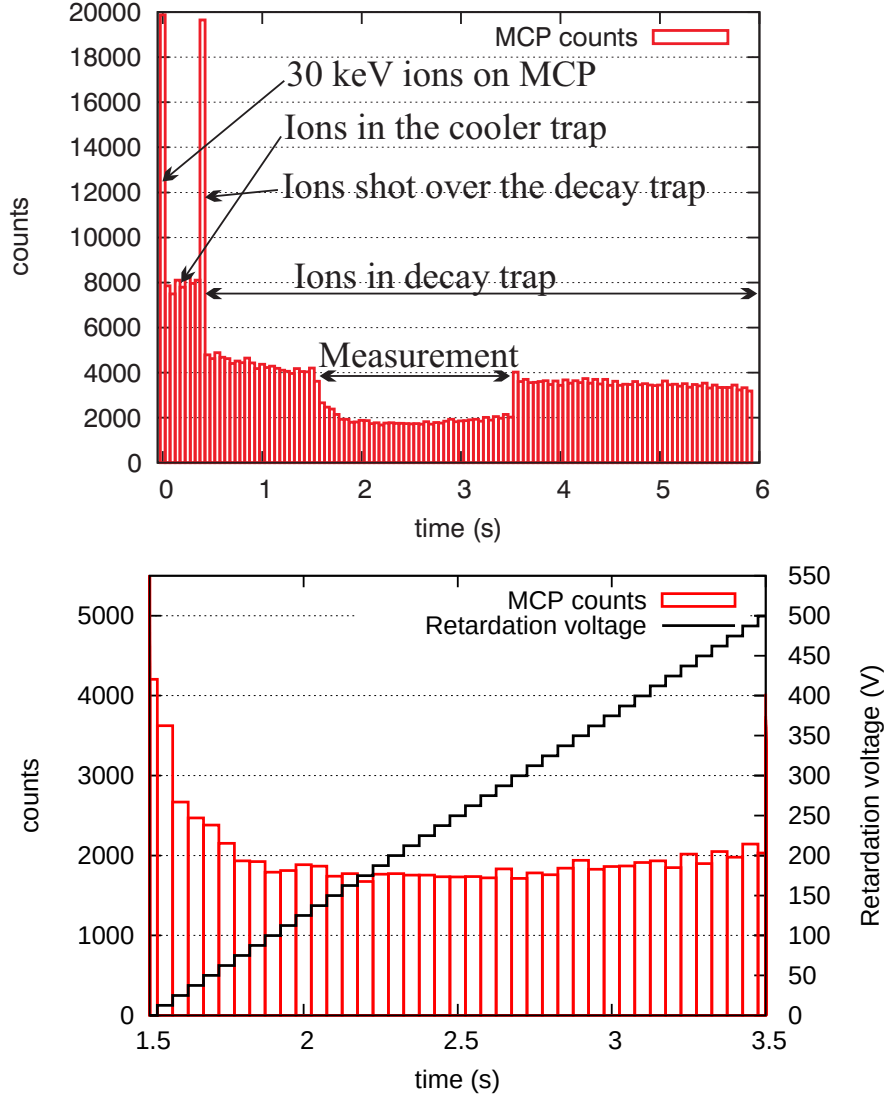


Figure 3.6 – Attempt at measuring a recoil ion energy spectrum in the decay of ^{35}Ar by ramping the spectrometer during one experimental cycle. The top panel shows the full experimental cycle with important events indicated on it. The two large peaks are ions shot over the decay trap (first 30 keV ions and then during the transfer from cooler to decay trap). The retardation voltage is kept at 0 V during the entire experimental cycle, except for the period indicated as ‘Measurement’. The bottom panel is a closer view of this period, during which the voltage on the retardation spectrometer is ramped from 0 V to 500 V in 12.5 V steps. Each bin is 0.05 s long, and during the ‘Measurement’ period each bin corresponds to a different retardation voltage.

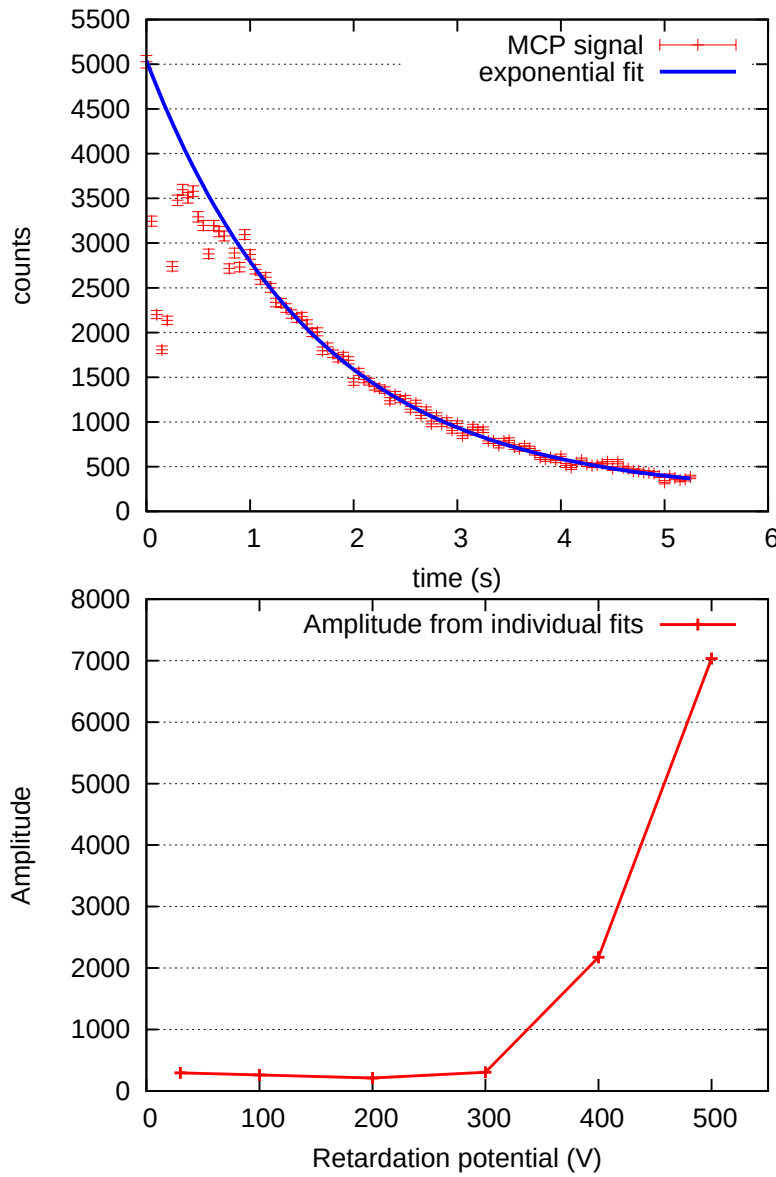


Figure 3.7 – ‘Recoil ion energy spectrum’ obtained by keeping the voltage on the retardation spectrometer constant during one experimental cycle. In the top panel, a spectrum is shown for a potential of 500 V on the retardation spectrometer. Without any disturbing ionisation effect this should show the exponential decrease of the β -background and possibly a small fraction of recoil ions that can pass the retardation barrier. In this measurement however, the half-life is 1.12(3) s with a reduced χ^2 of 2.13 in the range of 1–5.3 s. From many such measurements at different retardation voltages a retardation spectrum is constructed (bottom panel), by using the amplitudes of the exponential fits.

ions from REXTRAP, preparing them in the cooler trap and storing them in the decay trap for the measurement. This is repeated every few seconds to gather statistics. The energy of the recoil ions can be probed by switching the retardation spectrometer in different ways;

- During the measurement the retardation spectrometer is ramped from 0 V to 500 V.
- The retardation voltage can be kept constant for several experimental cycles. A means of normalisation is required for a detailed analysis of the data.

Both types of measurement were done during this run. Measurements performed using these two different experimental cycles are shown in figure 3.6 and figure 3.7. In figure 3.6 a full experimental cycle is shown in the top panel. The bottom panel is a close-up view of the period where the retardation voltage is ramped. An example of the second type of measurement, where the retardation voltage is kept constant, is shown in figure 3.7. The top panel shows the full experimental cycle for a retardation voltage of 500 V. The bottom panel shows a constructed recoil ion energy spectrum that was obtained by fitting the spectrum (of the top panel) with an exponential decay curve for the period when the ions are in the decay trap (> 1 s). The amplitude of this exponential curve, for different retardation voltages, then allows the reconstruction of a recoil ion energy spectrum.

To allow a more quantitative interpretation of the measured spectra and to compare the differences between the two types of measurements, one has to be aware of the different type of particles or events that contribute to the count rate on the MCP detector;

1. Random dark counts. They are caused by dark current within the MCP itself and is thus not influenced by other elements in the WITCH setup. These dark counts are randomly distributed in time.
2. Ions or electrons created in the system by field emission from electrodes. In principle randomly distributed, but small discharges can occur.
3. Ions or electrons created because of radiation after radioactive decay. This can depend on the voltages applied in the spectrometer as will be explained in chapter 5. This count rate can as well depend on the amount of ions in the decay trap, i.e. the activity of the radioactive source.
4. Recoil ions. Because integral spectra are measured at WITCH, the count rate of these decreases monotonically with increasing retardation voltage. The count rate of the recoil ions decreases exponentially in time at a constant retardation voltage.
5. β and γ particles created in the radioactive decay of ^{35}Ar . The signal of these is marginally influenced by the voltages in the spectrometer. The count rate of these decreases exponentially with time.

Neglecting item 3, data from measurements at a constant retardation voltage consist of a constant background (from items 1 and 2) and an exponentially decreasing signal from the recoil ions and β particles. Data from such a measurement can thus be fitted with an exponentially decreasing curve, where the constant background contains random ionisation and the exponential decay includes recoil ions and β particles. If the retardation voltage is changed, all contributions stay the same except for the one from the recoil ions. In addition, contributions from retardation- and activity-dependent ionisation can change a measured spectrum significantly.

One unusual feature that shows up when looking at the full experimental cycle (figure 3.6), is that there are more events registered on the detector when the ions are in the cooler trap than when they are in the decay trap. This could be caused by ionisation of the helium buffer gas due to γ radiation from the β^+ annihilation, by ^{35}Cl daughter ions from ^{35}Ar decay ionising the buffer gas, or by the fact that ions are lost during the transfer from the cooler trap to the decay trap. This large difference in count rate when the ions are in the cooler and decay trap was not observed anymore after the operation of the traps had been optimised further (figure 3.7), which might point to transfer losses. When the ions are in the decay trap, however, the count rate at 0 V cannot be fully attributed to recoil ions. The count rate of the recoil ions should not change much between 0 V and low retardation voltages (e.g. < 10 V), see figure 1.2. The only contribution that can change significantly between these two voltages are ions created upstream of the analysis plane.

A more strange result was produced when ramping the retardation spectrometer (see Fig. 3.6, bottom); i.e. the recoil spectrum obtained can again not be attributed to recoil ions. The number of counts first decreases in the interval from 1.5 s to 2 s – which is normal –, only to increase again after 2.5 s – which cannot be attributed to recoil ions. This count rate has to be attributed to ionisation effects that are dependent on the retardation voltage. Subsequent measurements (figure 3.7) to find out where this effect originates, indicate that the signal is strongly correlated with the retardation voltage. The observed half-life of the count rate in the period when the ions are in the decay trap, excluding the measurement period, is also not the correct one for ^{35}Ar ; it is 1.10(17) s which shows that there is an extra count rate not caused by the recoil ions or β particles.

Another recoil spectrum was measured using the other method; the retardation spectrometer was kept at a constant voltage during the full experimental cycle. This was done to exclude effects which could arise from ramping the retardation spectrometer. In this type of measurement a spectrum such as previously measured should be obtained (i.e. Fig. 3.6, top) excluding the ‘Measurement’ period. The results for this are shown in figure 3.7. One already striking result is that the decay curve does not correspond to ^{35}Ar decay (see Fig. 3.7, top). This is, however, not related to the effect of the reduced half-life measured by implanting on the MCP (discussed in the previous section 3.4.1), as the ions were kept in the decay trap for this measurement. The reason for this seems to be that the signal from the secondary ionisation depends on the amount of ra-

radioactive ions in the decay trap in a non-linear fashion. Half-lives ranging from ~ 1 s to ~ 2 s were measured. These data (figure 3.7, top panel) were optimised by looking at a specific time bin from the experimental cycle and plotting the different values obtained from different experimental cycles in a histogram; typically a spectrum such as shown in Fig. 3.7 (top) consists of 100 experimental cycles. In principle the counts from one time bin over the different experimental cycles should follow a normal distribution; outliers were removed from the data according to Chauvenet’s criterion [Anscombe & Guttman, 1960]. This is justified by the observation of small discharges on the detector that occurred from time to time. With this criterion outliers are rejected if the deviation from the mean has a probability lower than $1/2n$ with n the number of data points (i.e. in this case the number of files or experimental cycles). This yielded better fits in general, but still a large spread in the values of the half-life was observed; from 1 s to 1.7 s. By using this criterion the reduced χ^2 ’s were reduced from 2.2–7.10 to 1.16–1.96.

At higher retardation voltages it is clear that unwanted ions are created in the system; the count rate seems to increase steeply where it should decrease monotonically if the detected events would be recoil ions. But also at lower retardation voltages ionisation effects are at play. An indication for this is the fact that the count rate measured with a voltage of e.g. 0 V applied to the retardation spectrometer does not decrease in accordance with ^{35}Ar decay; the measured half-lives are less, using both measurement methods.

There is, however, one clear difference between ramping the spectrometer during one measurement cycle and keeping it constant. The increase in count rate at higher retardation voltages for the spectrum measured during one cycle is much lower than the count rate for the reconstructed spectrum; compare, for instance, the count rates at 400 V and 500 V. This indicates that the ionisation effect observed in figure 3.6 is not immediate, but needs some time to reach its maximum effect. This will be discussed in more detail in chapter 5. It is not possible to make quantitative conclusions about the data. In Fig. 3.7 it is clear the the signal-to-noise ratio at the higher retardation voltage is much lower than one. In Fig. 3.6 the situation is not that bad, but it is not possible to separate the count rate of the recoil ions and β ’s from the noise and ionisation effect.

After two radioactive runs (with ^{124}In and ^{35}Ar) the implemented improvements were evaluated and some more changes were made over the CERN shutdown period so as to further increase the reliability of the system.

3.5 2010: Electron Capture

The main goal of the run in June 2010 was to measure (mono-energetic) recoil ions resulting from electron capture decay which would allow calibrating the spectrometer and investigating some systematic effects. The primary candidate was ^{144}Eu , and the second in line was ^{140}Pm . Unfortunately the beam was heavily contaminated with other rare-earth isotopes – some of which were long-lived, thus reducing the activity in the decay trap –, whereas a relatively

(50 %) pure beam beam is required to measure data that can later be interpreted. A feasibility study was performed to see if another isotope could be found on this TaW target which could be used to measure recoils from electron capture. Additionally, before this run a fixed conductive wire was installed in the spectrometer as a first solution to solve the issue of the secondary ionisation (see chapter 5).

A run on an electron capture (EC) decay is important to measure the response function of the entire detection system. The decay of ^{144}Eu contains a 9.68(19) % electron capture branch; this provides a mono-energetic decay which has a higher energy than the β recoil endpoint – 149.0 eV versus 124.9 eV, respectively. The main parameters influencing the response function should be the dimensions and energy distribution of the ion cloud, the ratio of the magnetic fields and the electric potential in the spectrometer. Deviations from the expected response function will allow a characterisation of systematic effects in the system.

3.5.1 Measurement of a Recoil Energy Spectrum

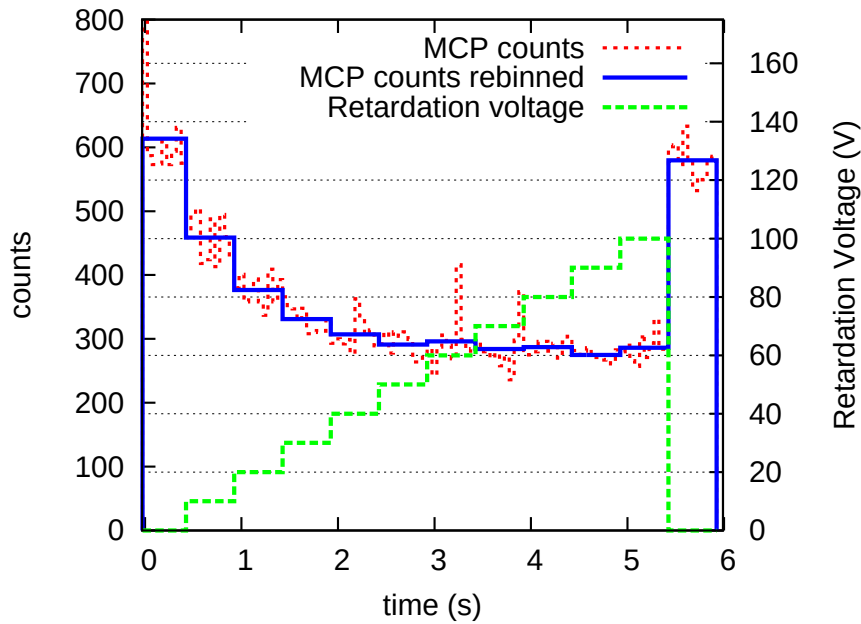


Figure 3.8 – Recoil spectrum measured during the electron-capture run. In the rebinned version, each bin corresponds to one retardation voltage. During the first and last bins (in the rebinned version) the spectrometer is at 0 V. The voltage is ramped from 10 V to 100 V in 10 V steps; this is shown on the right y-axis.

In spite of the low amount of recoil ions, some recoil ion energy spectra could

Table 3.2 – *The endpoint energies of the recoil ions and the position of the electron capture peak for isotopes in the mass 142 isobar. Only isotopes with a half-life between 1 s and 2 hours are shown.*

Isotope	Endpoint Energy (eV)	EC-peak position (eV)
¹⁴² Dy	163	191
¹⁴² Gd	55	72
¹⁴² Eu	193	223
¹⁴² Sm	9.3	17.7
¹⁴² Pm	69	87
¹⁴² La	94	-
¹⁴² Ba	27	-
¹⁴² Cs	230	-

still be measured. One of the spectra with an acceptable amount of statistics is shown in figure 3.8. A clear decrease in counts is seen until 50 V. The analysis of this spectrum is quantitatively not possible. First of all the beam composition is not known, and secondly, the charge state distribution of the daughter ions after the recoil is also unknown. Possible detected isotopes with their maximum recoil energy and EC-peak position are listed in table 3.2. For an electron capture decay it is expected that the daughter ions will typically have a higher charge state (e.g. 3^+ or 4^+). The reason for this is that during electron capture an electron from the inner electron shells is used for the decay. The subsequent Auger cascade will then release a few more electrons.

If one assumes a charge state of 4^+ for example, many recoil ions will be stopped already at 20 V. A few isotopes (i.e. ¹⁴²Dy, ¹⁴²Eu and ¹⁴²Cs) can account for the step from 40 V to 50 V.

3.5.2 Other Measurements

Some other results were obtained during this run as well. A degradation of the main MCP detector was e.g. detected (see section 6.3.3). During the preparation of the run this was not seen when working with small ion bunches. In the meantime a new detector is operational with a larger detection area; 8 cm diameter instead of 4 cm. It is currently being characterised, to be used in the next run on ³⁵Ar.

Also, the secondary ionisation has not been observed during this run. There may be two reasons for this. The implemented solution – a conductive wire (see section 5.4) – is working. However, since the activity of the source was rather low, the loading of the Penning-like trap was too slow to build up during a measurement and cause any noticeable effect.

The mass resolving power of the traps was also tested, in an attempt to obtain a pure source, see figure 4.10. This was not successful as the mixture of isotopes present in the traps have small relative mass differences. However, this was the first test of mass purification at WITCH under realistic conditions.

3.5.3 Conclusion

The main conclusion from this run with rare earth isotopes is that target development is still necessary. It is possible to selectively ionise the desired isotopes with the RILIS [Karlov et al., 1978]. However, the release from the other rare earth elements has to be reduced first, otherwise the selectively ionised elements will still drown in the background of other rare earth contaminations. The target group at ISOLDE is working on this problem, as these rare earth elements are also requested for other experiments. Unfortunately, the expected completion of a target being able to deliver a specific rare earth element is 3–5 years.

Chapter 4

Upgrade of the WITCH Setup

Following the ^{35}Ar run of 2007, it was clear that a serious upgrade of the WITCH setup was necessary. The setup had proven to allow a measurement of the recoil ion energy from ^{124}In decay, but a measurement with ^{35}Ar put more stringent constraints on the system. Argon is a noble gas, so the probability of neutralisation of argon ions had to be decreased. To this end a general improvement of the vacuum, and in particular of the buffer gas system, was planned. Even though the exact origin of the secondary ionisation was not known at that point, as many possible sources of it had to be removed. This included a lowering of the rest gas pressure, but also the removal of certain contaminating materials in the vacuum, and electropolishing of certain electrodes. This is described in section 4.1.

Other improvements were necessary to become independent from REX-ISOLDE and REXTRAP. Until recently all beams for WITCH, both stable beams as well as radioactive beams, were provided via the REXTRAP buncher. As REXTRAP is an essential part of the REX-ISOLDE post-acceleration setup, this significantly reduces the amount of time available for testing and optimising WITCH with stable beams. A way out of this was found by combining the WITCH surface ion source in the WITCH horizontal beamline with a new RFQ buncher. This provides ion bunches with similar properties as those coming from REXTRAP, allowing for testing all aspects of the WITCH experiment – from beam tuning to trap tests, independent of REXTRAP and REX-ISOLDE operations. However, it turned out that the stray field of WITCH at the position of the REX-ISOLDE mass separator, between the REXEBIS charge breeder and the RFQ post-accelerator, although only at the level of 5–10 G, seriously disturbed the transmission of the beams there. In addition, tests showed that the A/q scaling, that is a crucial element of the tuning of beams through the post-accelerator, was lost. Full independence from REX-ISOLDE operations thus required, apart from the WITCH RFQ buncher, also that the magnetic

stray field of WITCH be reduced. It was therefore decided to install a magnetic shield around the REX-ISOLDE setup. This should then significantly extend the time available for offline work with the WITCH magnetic field turned on. Previously stable beam tests at WITCH could only be performed during 3–4 weeks per year, usually to prepare online runs. It is clear that this is largely insufficient for efficient commissioning of a precision experiment as complex as WITCH. This upgrade is described in section 4.3.

Finally, other - not less important - improvements, were also installed during this time; a new method for β normalisation was implemented, a third magnet was installed in the system – a so-called compensation magnet –, the operation frequency of the pulsed drift tube was increased and the operation of the Penning traps has been significantly improved. The new normalisation method will allow a normalisation of the recoil ion energy spectrum by measuring a signal that is proportional to the number of ions in the decay trap; i.e. the amount of β 's transmitted from the decay trap into the vertical beamline. Initially this will give more flexibility by enabling new measurement cycles; e.g. a measurement cycle where the retardation voltage is not changed during one measurement cycle. Ultimately this normalisation might prove to be necessary to reduce systematic uncertainties. The installation of the compensation magnet removed a Penning-like trap which was situated in the re-acceleration section of the spectrometer. Thanks to this the re-acceleration electrodes can be operated at their design voltages, and moreover, it also helped in the reduction of ionisation in the system. The increased operation frequency of the PDT (from 1 to ~ 5 Hz) allows to accept more than one bunch per second from REXTRAP into the WITCH Penning traps. This effectively increases the transport efficiency of the system, and improves the number of ^{35}Ar ions that can be obtained from REXTRAP – which is, at the moment, limited by the charge exchange half-life of the argon ions in REXTRAP. This is described in section 4.2. Finally, the general operation of the Penning traps has been greatly improved thanks to new hardware and the control system. In particular ion clouds can be cooled much better now; they can be trapped with a trap depth below 1 V where this was 10 V a few years ago.

4.1 Vacuum Improvements

In a system at high vacuum or ultra high vacuum (UHV), the pressure in a volume is determined by three factors:

- The **pump capacity** or the rate at which molecules and atoms in the vacuum can be removed.
- **Outgassing** and **leaks** are sources of pressure increase. Leaks allow air getting into the system. Impurities present on the surface of the vacuum chamber and in the bulk of the vacuum components will be slowly released into the vacuum volume and contribute to the rest gas.
- The **vacuum conductance** describes how effective the pump capacity

is at some distance from the pump. A pump connected to the vacuum volume by a narrow tube is obviously not the most efficient solution. Ideally, one wants to have the pumps right next to the volumes where a good vacuum is required.

All three points were considered during the upgrade. The current lay-out of the vacuum system is schematically shown in figure 4.1. The most important changes in the system are

- the replacement of rotary pumps by oil-free scroll pumps as backing pumps,
- the inclusion of non-evaporative getter (NEG) coating and foil, providing a very large pumping capacity, at several places in the vacuum system,
- the installation of two NEG pumps in the beamline, and one NEG pump in the buffer gas system,
- and the installation of a gate valve in front of every turbo and NEG pump where this was not the case before.

Detailed information on the upgrades for an improved vacuum follows in the next sections. The results of the vacuum upgrades are presented in section 4.1.5.

4.1.1 NEG Vacuum Pumps

The selection of pumps for WITCH is not easy due to the presence of a relatively high stray field around the setup. This holds especially for the standard work horse for reaching a high vacuum, i.e. turbo molecular pumps, which have to be installed in a low magnetic stray field to avoid pump failure due to eddy currents. It was decided to deploy NEG pumps at critical positions in the setup where it was not possible to increase the pumping capacity with turbo molecular pumps due to the high magnetic stray fields; i.e. in positions close to the Penning traps.

The active material in NEG pumps consists of a ternary alloy that can adsorb all possibly types of gases except for noble gases and ammonia. The pumped gases are attached to the surface; eventually the surface of the NEG pump will be fully covered by the pumped gases and the pump is then saturated. It can then be re-activated by heating; typical temperatures needed are 200–700°C depending on the material. The bulk of the NEG pump material will then absorb the adsorbed layer from the surface and the surface can pump again. The NEG pumping material can be deployed in several ways;

- It can have the classical appearance of a pump, like a turbo pump, which is attached to the beam line. However, unlike a turbo pump a NEG pump does not contain any moving parts. Therefore, the NEG cartridge – which is the active part of the pump – can protrude into the vacuum system. This reduces the vacuum conductance of the pump. The pumping capacity when freshly activated is of the order of 400–2000 l/s, depending on the rest gas that is to be pumped.

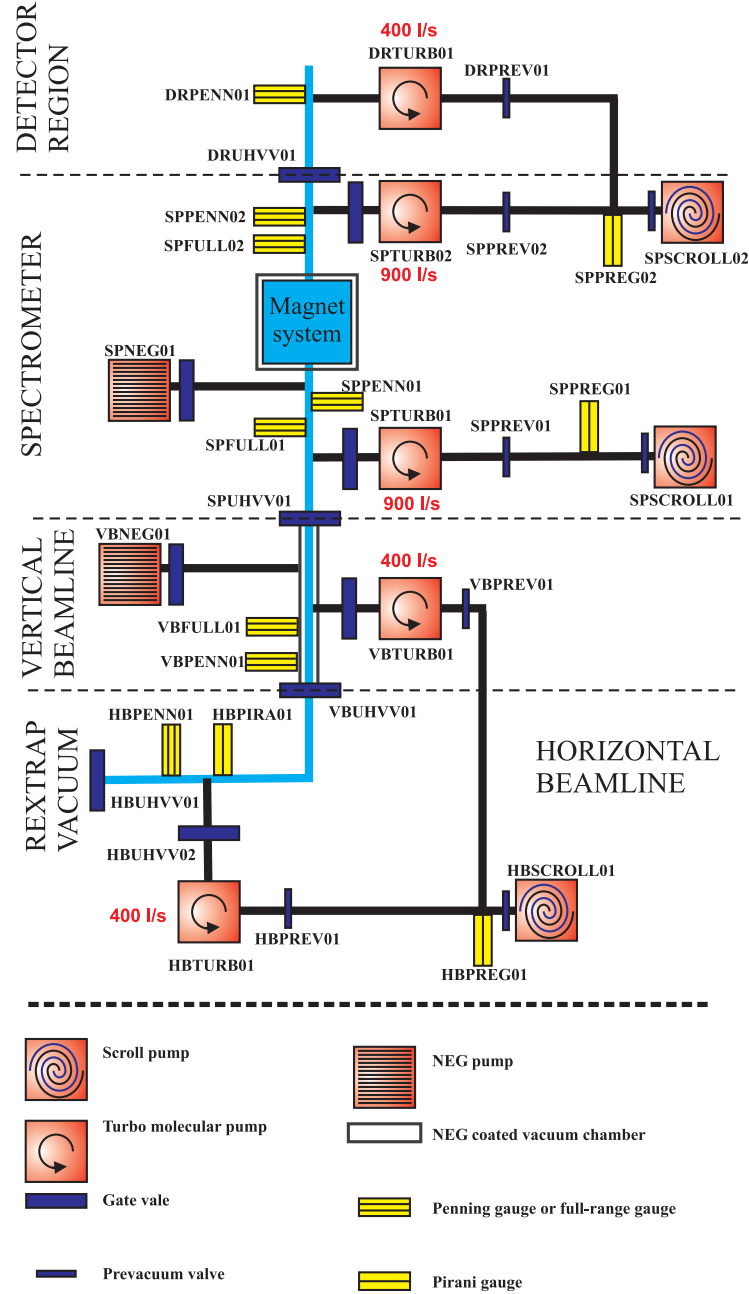


Figure 4.1 – WITCH vacuum system. The scroll pumps are from Varian, type ‘TriScroll 300’. The turbomolecular pumps are made by Adixen, type ATP400 and ATP900. The NEG pumps are made by the SAES Getters Group of type ‘GP 200 MK5’. The lay-out of the vacuum system before the upgrades can be seen in Ref. [Kozlov, 2005, p. 60].

- The NEG material is also commercially available as strips which can be mounted inside the system. The most common way to activate the material in this configuration is resistive heating. The mounting and activation of this type of strips was considered for WITCH, but discarded because of technical difficulties to mount them in an already densely-filled system.
- A recent development at CERN is the application of NEG material directly to the vacuum chamber inner walls; a so-called NEG coating. This has the advantage that the pump is placed exactly where it is needed, ensuring a good vacuum conductance. Heating and activation is done externally by baking the system. The St707 material developed by the SAES Getters Group [SAES Getters Group, 2011] consists of 70 % zirconium, 24.6 % of vanadium and 5.4 % of iron and is activated at around 400 centigrade. To obtain low activation temperatures special materials have been developed at CERN which can already be activated at a mere 180 °C [Benvenuti et al., 2001]. This material contains titanium instead of iron and the abundances are also different [Benvenuti et al., 2001]. Six kilometres of vacuum chambers of the Large Hadron Collider (LHC) at CERN have been coated with this type of NEG material, see Ref. [Chiggiato & Costa Pinto, 2006].

Two NEG pumps are attached to the WITCH beamline. Also several vacuum chambers in the vertical beamline have been coated with the same NEG material as used in the LHC. Within the bore tube of the magnet it was not possible to add a NEG coating because of the required activation temperature which would cause a too large liquid helium consumption and might cause damage to the magnet. However, foils with a NEG coating were inserted around the main retardation electrode and the trap structure to provide additional pumping within these volumes as well. The NEG foils can be activated via vacuum heaters. The location of the various NEG pumps and coatings can be seen in Fig. 4.1.

With the inclusion of NEG material in the system, maintenances have to be planned more carefully as the activation of the NEG material is not a trivial procedure and an accidental venting of the system can saturate the NEG surface. Extra gate valves have been installed before these NEG pumps so that they do not get immediately saturated when the system is opened.

Finally, it has to be noted that fluor and other halogens are fatal for NEG material. It cannot get absorbed in the bulk upon activation and will thus permanently reduce the pumping capacity of the NEG material [Costa Pinto, 2010]. Fluor can be released in the system when teflon – a commonly-used insulation for electrical wire – is baked. Special care therefore had to be taken that all teflon was removed from the areas with NEG material. The same is true for oil which can end up in the system by using rotary pumps as backing pumps.

4.1.2 Vacuum Purity

The outgassing rate from the materials used inside the setup needed to be reduced to realise a lower pressure and a more pure vacuum. Several steps were taken to realise this.

First of all the backing pumps for the turbo pumps used to be rotary pumps that use oil as a lubricant. This is present in the backing lines as oil vapour. Normally this should not penetrate into the main vacuum if everything is set up correctly. However, experience shows that this is not the case. Needless to say, oil vapour is not something that is desired in a vacuum system. Therefore all rotary pumps have been replaced by ‘dry’ scroll pumps that do not contain oil for lubrication. They do contain some teflon to reduce friction of mechanical components. This can also end up in the backing lines, but luckily only in the form of a powder, thereby not affecting the vacuum.

Secondly, all vacuum components were treated with special care. Handling of vacuum components with gloves and cleaning them with ethanol belongs to the standard procedure. Additionally all components that are present in the system – with the exception of the horizontal beamline – have been cleaned in an ultrasonic bath. Such an ultrasonic bath creates small bubbles that implode on the surface of the components thereby clearing away surface impurities. The cleaning procedure consisted out of two steps. The first step is to clean the components in an almeco solution at 80 °C and the second step is to make sure that traces of the soap are gone in a distilled water bath at 80 °C.

Lastly, the materials for the vacuum were chosen carefully. All teflon – which served as an insulation for electrical wires and also as an insulator in the support structures of some beamline electrodes – had to be removed from the system because it would otherwise significantly reduce the effect of the NEG material. Moreover, polymers consist out of large molecules that can easily trap water and other contaminations in the bulk of their volume. These trapped contaminants will later outgas from the host material into the vacuum. In principle the only materials that should be used in an ultra-high vacuum system are certain metals (see table 4.1), ceramics and glass. But there are some exceptions to the pure materials; this has to do with the vapour pressure of a material. Vapour pressures of relevant materials are shown in table 4.1. As can be seen the vapour pressure of Zn at 500 K is higher than normal rest gas pressures during operation of the system (i.e. $\sim 10^{-9}$ mbar). This means that the material will be released in significant quantities during the bake-out and will thus add to the contaminations in the system when it is cold again.

On the other hand, some polymers are more suitable than others for use in a UHV environment: kapton (a polyimide film) and PEEK (polyether ether ketone) are routinely used in UHV environments. Kapton is used for electrical wire insulation and PEEK is used where insulators are required in the support structures. Some additional constraints for the material selection at WITCH exist. The materials need to be non-ferromagnetic – for use in the magnet bore tube – and be able to resist both high temperatures (~ 500 K) during a bake-out and low temperatures (~ 220 K) as are present in the bore tube.

Table 4.1 – Estimated vapour pressures of some materials. The values are extrapolated using the function $\log p_{mm} = A - B/T + C \cdot T + D \cdot \log T$ where A , B , C and D are coefficients that can be found in [Nesmeianov, 1963] and p_{mm} is the pressure in Torr. The coefficients were obtained by fitting experimental data.

Material	Vapour pressure at 300 K (mbar)	Vapour pressure at 500 K (mbar)
Fe	$3 \cdot 10^{-60}$	$7 \cdot 10^{-32}$
Ti	$1 \cdot 10^{-74}$	$4 \cdot 10^{-40}$
Cu	$4 \cdot 10^{-49}$	$5 \cdot 10^{-26}$
Au	$1 \cdot 10^{-52}$	$1 \cdot 10^{-28}$
Al	$9 \cdot 10^{-45}$	$2 \cdot 10^{-22}$
Be	$7 \cdot 10^{-47}$	$1 \cdot 10^{-24}$
Zn	$3 \cdot 10^{-14}$	$3 \cdot 10^{-5}$
Cd	$3 \cdot 10^{-11}$	$2 \cdot 10^{-3}$
Pb	$4 \cdot 10^{-26}$	$2 \cdot 10^{-12}$

4.1.3 Buffer Gas System

Since the prime physics candidate, ^{35}Ar , is a noble gas, special care has to be taken to avoid neutralisation of the ions of interest. At low energies argon ions cannot be neutralised by helium or neon, but all other atoms can neutralise argon ions. The neutralising contaminations can come from the vacuum rest gas pressure, but they can also come into the system as impurities in the helium buffer gas. The effect of impurities in the buffer gas can even be significant. Typical buffer gas pressures for the operation of the cooler trap are estimated to be in the region of 10^{-5} – 10^{-4} mbar. This corresponds to $2.5 \cdot 10^8$ – $2.5 \cdot 10^9$ particles in one cubic millimetre. Using gas from a He-57 bottle¹ as buffer gas this amounts to 750 to 7500 impurities in one cubic millimetre. Ion clouds in WITCH are usually larger than one cubic millimetre – this depends on the preparation –, so it is not unlikely that there is roughly one impurity for each argon ion. With many ion–buffer gas collisions occurring, the probability of charge exchange will then be significant.

Additionally, the purity of the complete buffer gas system is also important. When the buffer gas crosspiece is not filled with helium and when it is opened to the trap vacuum, it does not adversely affect the vacuum of the traps, even if pressures in the buffer gas crosspiece are in the 10^{-6} – 10^{-5} mbar range. This can be explained by the dominating gas flow in that region, i.e. a molecular flow. Since the buffer gas crosspiece is connected to the trap vacuum by a bellow-like tube, the probability for a rest gas atom to travel from the buffer gas crosspiece to the trap volume is low. However, things change when there is a flow of helium gas. A typical pressure in the buffer gas crosspiece during normal trap operation is $2 \cdot 10^{-2}$ mbar. The gas flow in that pressure region is a Knudsen flow (in contrast to the molecular flow at lower pressures), because the mean free path of the helium buffer gas atoms has dimensions similar to the vacuum

¹He-57 gas contains 3 contaminating atoms for every one million helium atoms

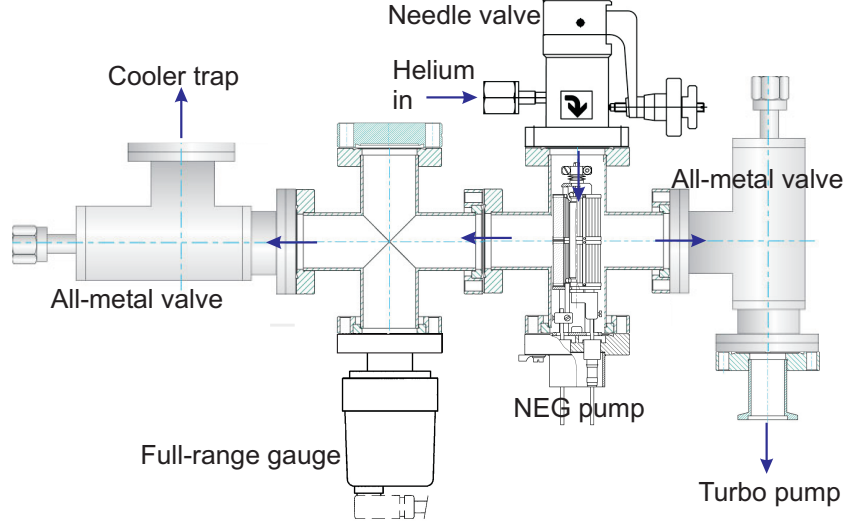


Figure 4.2 – A schematic representation of the buffer gas crosspiece used from the ^{35}Ar run in 2009 onwards. The connection to the cooler trap is made by a ~ 40 cm long UHV bellow followed by 50 cm of electropolished tube with a diameter of 6 mm. The helium flow is indicated by the arrows. The turbo pump is only used when activating the NEG pump.

vessel;

$$l = \frac{kT}{\pi\sqrt{2}d^2p}, \quad (4.1)$$

with l the mean free path, k the Boltzmann constant, T the temperature in Kelvin, d the molecular diameter and p the gas pressure. The mean free path for N_2 atoms with a Vanderwaals radius of $155 \cdot 10^{-12}$ m at a temperature of 293 K and a pressure of $2 \cdot 10^{-2}$ mbar, is $1.89 \cdot 10^{-2}$ m. Contaminations present in the buffer gas crosspiece will then rather easily be carried into the cooler trap by the helium flow. With a good base level of the vacuum in the cooler trap and purified helium buffer gas, this would then be the limiting factor in avoiding charge exchange of argon ions.

The first priority in minimising the charge exchange of argon ions was to construct a buffer gas crosspiece with as low a rest gas pressure as possible. A scheme of the current buffer gas crosspiece is given in Fig. 4.2. Its main features are that no polymer components are used, an *in situ* NEG pump and two manual all-metal valves to close it off from the main system and to provide access for a turbo pump. The NEG pump absorbs contaminations and does not affect the helium. As such it acts as a pump to reduce the base pressure, but additionally it will also absorb impurities in the helium gas coming from the He-57 bottle into the buffer gas crosspiece. In this configuration a base pressure of $5 \cdot 10^{-9}$ to $1 \cdot 10^{-8}$ mbar is typically achieved after activation. Measurements (see section

4.1.5) confirmed that these improvements eliminated the problematic charge exchange of argon ions in the cooler trap.

4.1.4 Electropolishing

Electropolishing is an electrochemical technique which smoothens the surface of a metal in the micrometre range. The component to be smoothed is immersed in an electrolyte solution – typically an acid solution – and a current is created between the component (anode) and an auxiliary electrode (cathode). This current is formed by ions from the component being oxidised and dissolved in the electrolyte. The reverse process can be used to coat the surface of a metal and is called electroplating. The transport of ions – and thus the smoothing of the surface – is largest where the electric field gradient is highest: at tips and sharp edges. An overview of the technique is given in Refs. [Landolt, 1987, Landolt et al., 2003].

The main aim of the electropolishing was to smoothen out the electrode surface – thus reducing the electrode surface area – to reduce the outgassing rate and the field emission from the electrode surface. The electropolishing treatment was applied to the electrodes in the re-acceleration section of the spectrometer. Reducing the field emission of electrons from the smoother surfaces also reduces a potentially unwanted background and decreases the rate at which particles in Penning-like traps can ionise the rest gas (see section 5.1).

The results of the electropolishing cannot be evaluated independently, since the electrodes were installed at the same time as other upgrades. The vacuum in the spectrometer section has improved (see section 4.1.5 and table 4.2). The high voltage performance of the re-acceleration electrodes was improved by the installation of an additional magnet, as discussed in section 4.2.2. Further, also the creation of unwanted ionisation in the system was lowered (see section 5.2.3).

4.1.5 Results

A few results of the vacuum upgrades are listed in this section. The better rest gas pressures in the system are shown, an example of how well the NEG coating behaves and the fact that charge exchange of noble gases is not a problem anymore in the WITCH cooler trap.

Vacuum levels

In table 4.2 the vacuum in different parts of the system before and after the upgrades is shown. The vacuum has improved everywhere – except in the horizontal beamline where nothing was changed –, and most noteworthy is the improvement in the PDT section. This is due to the replacement of a big support piece made of teflon by a PEEK structure and the inclusion of NEG coating and a NEG pump. The improved vacuum in the vertical beamline (see ‘Below cryostat’ and ‘PDT section’ in table 4.2) is beneficial for avoiding charge ex-

Table 4.2 – Vacuum levels before and after the upgrades

System section	Old pressures	New pressures
HBL	$1 \cdot 10^{-8}$ mbar	$1 \cdot 10^{-8}$ mbar
PDT section	$1 \cdot 10^{-7}$ mbar	$4 \cdot 10^{-10}$ mbar
Below cryostat	$\sim 5 \cdot 10^{-8}$ mbar	$5 \cdot 10^{-9}$ mbar
Above cryostat	$2 \cdot 10^{-8}$ mbar	$5 \cdot 10^{-9}$ mbar

change of argon ions in the cooler trap. The slightly improved vacuum in the spectrometer, i.e. ‘Above cryostat’ in table 4.2, is expected to help in reducing the secondary ionisation.

Effectiveness of NEG coating

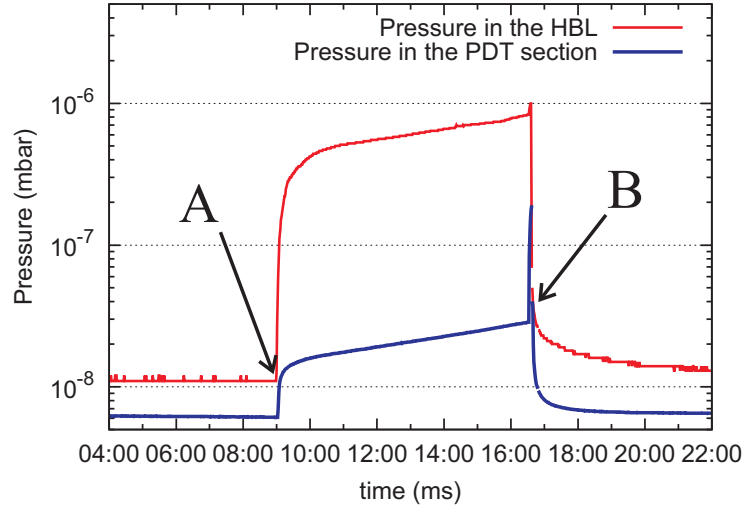


Figure 4.3 – An example of the effectiveness of the NEG coating. Shown in the graph are the pressures in the horizontal beamline and the PDT section during one day. The former does not contain any NEG coating, the latter does. During this day all valves in front of the pumps (both turbo pumps and NEG pumps) were closed (arrow **A**) and reopened almost 8 hours later (arrow **B**). The pressure in the HBL increased by almost two orders of magnitude due to outgassing of components, while the pressure in the PDT section is not increased by even one order of magnitude and it stayed below $2 \cdot 10^{-8}$ mbar.

The effectiveness of the NEG coating was proven during a maintenance of the pressurised air system. Without pressurised air all valves – including the valves of the turbo and NEG pumps – were closed. The only ‘pump’ present in the system was the NEG coating in the PDT section. In figure 4.3 the pressures in the horizontal beamline and the pulsed drift tube section are shown during that

day. The sharp increase of the pressure occurs at the start of the maintenance. The pressure in both volumes increases during the day due to outgassing. The pressure in the PDT section remains quite good (low 10^{-8} mbar level) due to the presence of the NEG coating here that continues to pump. However, the pressure in the horizontal beamline, where no NEG coating was installed, immediately jumps to the 10^{-6} – 10^{-7} mbar region. This ‘experiment’ shows that the NEG material in the pulsed drift tube section was successfully activated at that point and, most importantly, that the NEG coating provides a substantial amount of pumping capacity.

Charge Exchange

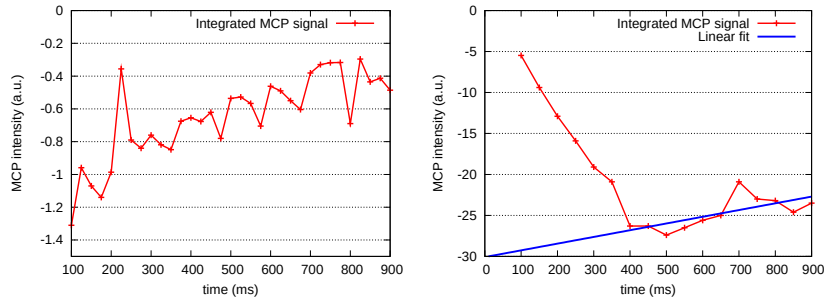


Figure 4.4 – Left: The charge exchange of ^{20}Ne in the cooler trap. The integrated MCP signal (more negative means more counts) is shown as a function of the time the ^{20}Ne ions spent in the cooler trap. The lines are to guide the eye. **Right:** The charge exchange of ^{36}Ar in the cooler trap. The fitted slope is $-0.008(3)$ intensity/ms. The reduced χ^2 of the fit is 2.2, which can be attributed to a lack of uncertainties on the measured points. The fitted slope corresponds to losses of $15(6)\%$ /500 ms or a charge exchange half-life of ~ 1.666 s. The increase of the ion signal in the first 400 ms is due to the cooling down and centring of the ions. At 400 ms the ions are fully centred in the cooler trap. A small decrease of the signal – i.e. loss of ions – can be seen. However, this needs to be compared to the 8 ms charge exchange half-life of ^{35}Ar during the run in 2007.

After the bad experience with a charge exchange half-life of 8 ms for ^{35}Ar in 2007 and the subsequent improvement of the vacuum to avoid this, the new measurements of the charge exchange half-life were expected eagerly. First the charge exchange half-life with ^{20}Ne – ionised buffer gas from REXTRAP – was measured. The result was positive; yielding a charge exchange half-life of the order of 500 ms (see Fig. 4.4). For ^{36}Ar an even better result was obtained (^{20}Ne is more susceptible to charge exchange due to its higher ionisation potential); the loss of argon ions was measured to be $15(6)\%$ in 500 ms which corresponds to a charge exchange half-life of 1.19–2.77 s (see Fig. 4.4). This means charge exchange losses are almost negligible for a normal operation with WITCH; typical preparation times in the cooler trap are of the order of half a second for lighter

ions (e.g. ^{35}Ar and ^{39}K) to one second for medium-weight ions ($100 < A < 150$, e.g. ^{133}Cs and ^{144}Eu).

4.2 Increased Flexibility and Improved Operation

Upgrades increasing the flexibility of the experimental cycle and improving the operation of the system have been performed during the upgrade campaign as well. The repetition rate of the experiment was limited in the past by the repetition rate of the switching of the pulsed drift tube. This has been increased, which allows to load the traps several times in one experimental cycle – and thus have a higher number of statistics – and to increase the efficiency of beam tuning. Also, a third magnet has been installed in the setup which allows the voltage on all re-acceleration electrodes to be ramped to their design values. A new method of normalising the count rate of a recoil ion energy spectrum is in an advanced stage of development. The normalisation will allow to use different measurement cycles to obtain a recoil ion energy spectrum; i.e. with this it is possible to keep the retardation potential during one experimental cycle constant instead of having to ramp it from the minimal to the maximal value in a few seconds. In this way some systematic uncertainties – e.g. due to ion losses from the decay trap – can be avoided. Finally, the optimisation of the traps is also described; mainly the characterisation of the traps using rf excitations and the optimisation of the energy distribution will be discussed.

4.2.1 PDT Repetition Rate

As mentioned in the previous section, a limitation for the experiment was the neutralisation of ions with a high ionisation potential. Thanks to the upgrades made in the WITCH setup this problem belongs to the past for an initial measurement, however, it is still an issue in the REXTRAP setup where it was impossible to make significant upgrades. Hence, accumulation times exceeding 100 ms are not useful in REXTRAP when working with ^{35}Ar , because of a ‘charge exchange half-life’ of ~ 70 ms. There are two options to circumvent this problem.

- One is to use the cooler and buncher of the HRS separator, ISCOOL, and thus only shoot through REXTRAP. Since the operation of WITCH is completely tuned to the properties of REXTRAP this would require a significant amount of extra testing and optimisation time. E.g. the bunches from ISCOOL do not have the right time structure for WITCH at the moment (e.g. see Ref. [Mané et al., 2009]).
- The other option is to increase the repetition rate of the WITCH setup and more specifically that of the PDT, thus allowing to accept several bunches from REXTRAP during one experimental cycle. The repetition

rate of the PDT is determined by the electronics used for switching the PDT.

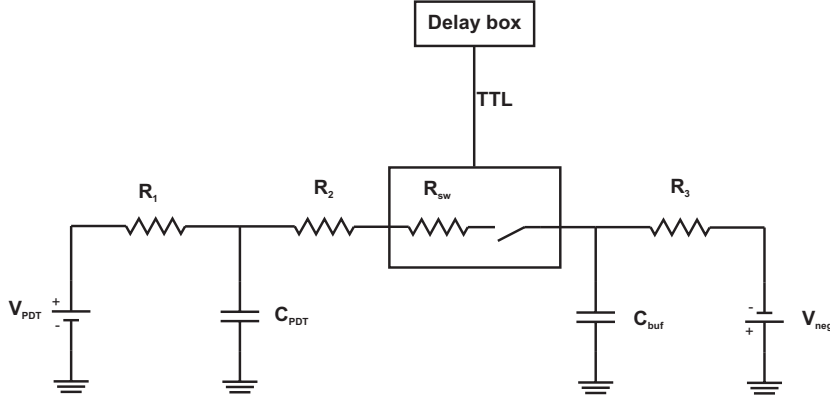


Figure 4.5 – The electronics scheme for the operation of the pulsed drift tube. Original values for the components are; $R_1 = 500 \text{ M}\Omega$, $R_2 = 1500 \Omega$, $R_3 = 2000 \Omega$, $R_{sw} = 360 \Omega$, $C_{PDT} = 100 \text{ pF}$ and $C_{buf} = 94 \text{ nF}$. C_{PDT} is the pulsed drift tube electrode.

The electronics scheme of the pulsed drift tube and specifications of the components are given in Fig. 4.5. The positive voltage of the PDT is supplied by a FUG HCP 140-65000 (65 kV, 2 mA) and the negative side by an ISEG CPn 100 105 24 5 (−10 kV, 1 mA). The switching is realised by a solid state switch from Belhke, model HTS650-03-LC (maximum peak current that can be handled is 30 A). The electronics scheme allows the following mode of operation. V_{neg} is loading the capacitor bank C_{buf} . When a trigger is given to the HV switch, electrons from C_{buf} will flow to the pulsed drift tube, C_{PDT} . When the switch is closed, V_{pos} will ramp the pulsed drift tube to its original positive potential and the capacitor bank will be reloaded.

Increasing the repetition rate

The time constants for the ramping up and ramping down of the pulsed drift tube and capacitor bank are defined by the passive components in the system: resistors and capacitors. The time constant for ramping down the PDT is

$$\tau_{PDT} = (R_2 + R_{sw}) \cdot \frac{C_{buf} \cdot C_{PDT}}{C_{buf} + C_{PDT}} \approx (R_2 + R_{sw}) \cdot C_{PDT} \quad . \quad (4.2)$$

For the values given in figure 4.5 this leads to a time constant of $0.186 \mu\text{s}$. This is sufficiently fast to efficiently pulse down a typical ion bunch in WITCH. The amount by which the repetition rate of the PDT can be increased depends on how fast the capacitor bank can be charged, and how quickly the PDT can ramp

from its low value after the switching to its original positive value. The former is characterised by the time constant

$$\tau_- = R_3 \cdot C_{buf} \quad , \quad (4.3)$$

while the latter is characterized by

$$\tau_+ = R_1 \cdot C_{PDT} \quad . \quad (4.4)$$

In principle one can freely choose these components and their respective values, but some experimental constraints need to be considered. The power supplies can only provide a certain current which limits the ramping up or ramping down times. To protect the power supplies, the resistors R_1 and R_3 are included so as to limit the current to be delivered by the power supplies. With the current hardware the lowest value is given by $R_1 = \Delta V / I = 30 \text{ kV} / 2 \text{ mA} = 15 \text{ M}\Omega$. For R_3 the voltage drop during the switching is about 30 V, which leads to a minimum resistance of 30 k Ω . With the current hardware the time constant for the ramping up of the PDT is $\tau_+ = 1.5 \text{ ms}$ and the loading of the capacitor bank has a time constant of $\tau_- = 3 \text{ ms}$. This is fast enough to operate the PDT at a rate of even 30 Hz (assuming that a recovery time of $10 \cdot \tau$ is required, which yields a precision on the voltage of $\delta V = 5 \cdot 10^{-5}$).

Note that the main limitation for an increased operation rate of WITCH is now not anymore determined by the PDT and its electronics, but by the time it takes to cool the ion cloud into the quadrupole potential of the cooler trap. Whenever a new bunch of ions comes into the cooler trap for accumulation, the voltage on the lower endcap electrode of this trap needs to be decreased to accept the new ions. When the old ions have not cooled into the quadrupole potential – formed by the central electrodes of the trap – they can escape the trap when the voltage on the lower endcap electrode is decreased. During the preparation of the radioactive run in July 2010 it was possible to achieve a repetition rate of 5 Hz with ^{39}K ions, as they were sufficiently cooled after $\sim 150 \text{ ms}$. The buffer gas pressure in the buffer gas cross piece was $2 \cdot 10^{-2} \text{ mbar}$. This 5 Hz repetition rate could not be achieved anymore with heavier ions, such as ^{133}Cs , as they require a longer time to be sufficiently cooled. This can be compensated by allowing a higher buffer gas pressure in the cooler trap, but one has to be careful as this will also increase the pressure in the decay trap and the spectrometer. If this pressure is too high it can distort the recoil ion energy spectrum and induce discharges in the cooler trap as well.

The achievement of a higher repetition rate for the PDT is an important step, as it will increase the amount of (^{35}Ar) that can be trapped in the WITCH setup. The limitation coming from the charge exchange half-life of ^{35}Ar at REXTRAP ($\sim 70 \text{ ms}$) has thus been improved; at a repetition rate of 5 Hz, five times more ions can be trapped. Taking into account an ^{35}Ar yield of 10^6 – 10^7 ions/ μC from ISOLDE and a REXTRAP efficiency of 50 %, the WITCH Penning traps can be filled with an amount of ^{35}Ar ions that is close to the space charge limit of 10^6 ions in the Penning traps. But also for elements that do not experience charge exchange so rapidly, the increased repetition rate is beneficial; less intense ion bunches ($< 10^6$ ions/bunch) from REXTRAP typically have

Table 4.3 – *Settings for the voltages applied to re-acceleration electrodes in the spectrometer. High voltages (≤ -8 keV) on the re-acceleration electrodes are required to properly focus recoil ions on the main MCP detector.*

Electrode	Design value (kV)	Typical settings in the past (kV)	Typical settings now (kV)
SPACCE01	-2	-1.4	-2
SPACCE02	-10	-1	-9
SPEINZ01	-0.2	-0.2	-0.6
SPDRIF01	-10	-0.55	-9
SPDRIF02	-10	-7	-9

better beam properties – which lead to a better efficiency of injecting the ions into the magnetic field of the Penning traps – than highly intense ion bunches (10^7 ions/bunch) and it is thus preferential to load the cooler trap several times instead of accepting one intense ion bunch (see Ref. [Ames et al., 2005] for an example of the dependence of the transversal emittance as a function of the number of ions per bunch).

4.2.2 Compensation Magnet

Another major improvement of the setup is aimed at ramping up the re-acceleration electrodes to their design values. The biggest hurdle was to ramp up SPACCE02 and SPDRIF01. The design value of -10 kV for those two electrodes was not attainable with the magnetic field switched on. At around 3–4 kV the power supply for SPDRIF01 would trip. The reason for this was found to be the fact that SPACCE02, SPEINZ01 and SPDRIF01, along with the magnetic field in that region, form a Penning-like trap for electrons. Ideally this trap should not get filled with electrons, but electrons created by field emission from the electrodes will be trapped in there. The higher the voltage on SPACCE02/SPDRIF01, the deeper this Penning-like trap for electrons is. With a growing amount of electrons in the trap, the amplification of the charge carriers increases. At a certain point the amplification will be sufficiently high to have a self-sustained discharge in that trap. When the amount of electrons becomes too large, they can interfere with the operation of the power supplies via discharges (i.e. causing them to shut down or trip). The solution was to eliminate the Penning-like trap in this region.

Since the voltages on the re-acceleration electrodes could not be changed without changing the focussing properties, the magnetic field in the region had to be altered. This was realised by installing a third magnet in the system. The magnetic field, both with and without this extra magnet, is shown in figure 4.6. As can be seen in the figure with the compensation magnet switched on, the magnetic field does not connect the two regions with high negative potential (labelled as ‘Post acc.’ and ‘Drift Electrodes’) anymore, so that the Penning-like trap is avoided and no more discharges can occur.

This so-called compensation magnet consists of 2748 windings. The nominal

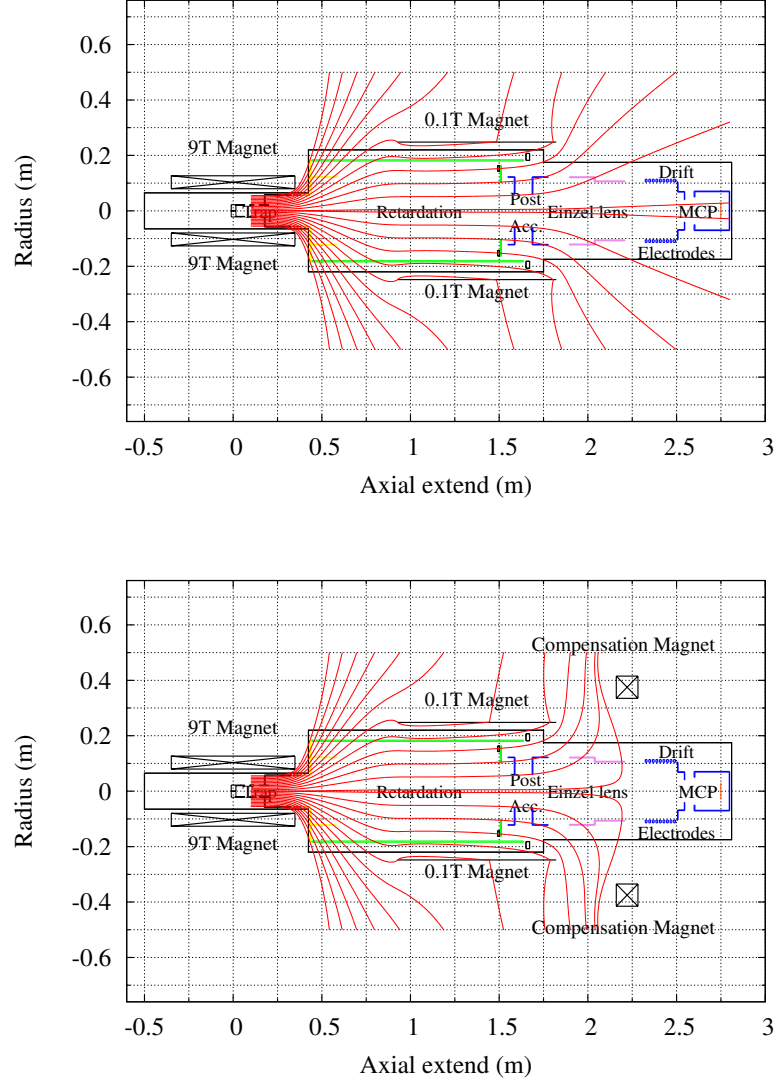


Figure 4.6 – Representation of the magnetic field lines in the trap and spectrometer region. The top figure shows the field lines without compensation magnet (at $z = 2.25$ m), the bottom figure shows the same with compensation magnet. ‘Post Acc.’ refers to SPACCE01 (left) and SPACCE02 (right). ‘Einzel lens’ is SPEINZ01. The ‘drift electrodes’ are SPDRIF01 (left) and SPDRIF02 (right). From Ref. [Friedag,].

current of 2.877 A – which corresponds to a voltage of 133 V – creates a field of 0.00167 T (17 G) by itself. This field is high enough to reverse the magnetic field in the region of the einzel lens electrode. As shown in table 4.3 the objectives of being able to run the re-acceleration electrodes in the spectrometer at about their design values were met with the installation of this compensation magnet.

4.2.3 β Normalisation

As mentioned in section 2.6 different experimental cycles can be utilised for the measurement of a recoil ion energy spectrum. The one used almost exclusively until now is a cycle where the retardation potential is ramped over the full range in one measurement cycle. Proper normalisation of the spectrum is then done by correcting for the half-life. This requires that there are no losses from the decay trap and that the half-life is known with good precision and accuracy; the latter is the case for ^{35}Ar . Another operation mode is to keep the retardation potential constant during one experimental cycle and only change the retardation potential every few cycles. The advantage of this mode is that this might remove possible unwanted effects related to the ramping of the retardation potential and reduce systematic effects. Also, the same statistics is now accumulated for all retardation voltages, whereas with the other mode more statistics is gathered for the voltages that are applied first. The disadvantage is that the number of ions in the decay trap can fluctuate between different experimental cycles; hence the need for a measurement of the amount of ions in the decay trap or an observable that is proportional to this amount.

Several ideas to obtain a normalisation have been proposed in the past. PIN diodes located inside SPDRIF01, close to the main detection MCP, were considered for the detection of β 's. This idea was abandoned because of the low solid angle of the β 's and sparking problems. A scintillator between the cooler and decay trap was also considered. This was finally not implemented due to the bad vacuum properties of the optical fibres and the difficulty of coating the scintillator with a conductive layer. A conductive layer is required not to disturb the operation of the traps. Currently the problem is attacked from a new angle. The idea is to measure the number of β 's coming from decays in the decay trap at the position of VBDIAG03 (Fig. 2.3). This position was chosen for practical reasons and because the magnetic stray field in that region is high enough to focus the β 's coming from the decay trap such that enough statistics for the normalisation can be acquired. A system consisting of a PIN diode array with in its centre a smaller version of VBEINZ01 has been installed (Fig. 4.7).

Several tests towards the full implementation of this system have been performed. First of all the basic idea – the detection of β 's in the VBL – had to be checked. To this end one PIN diode on a moveable feedthrough was installed at the position of VBDIAG03 (see Fig. 2.3) allowing a measurement of the distribution of the β 's in the horizontal plane. This was done both in a 6 T and 9 T magnetic field. The source was an off-line ^{90}Sr source positioned in the decay trap at the same position as the ion cloud with an activity of ~ 200 kBq. The size of the deposited activity was $1 \div 2$ mm. The measured distributions are

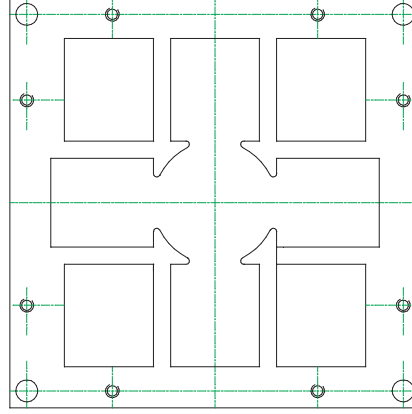


Figure 4.7 – Schematic drawing of the support for the PIN diode array. In the centre a smaller version of VBEINZ01 is situated. In the square holes eight PIN diodes with a surface of 1 cm^2 are installed.

shown in figure 4.8. The maxima of the two distributions are not coinciding, which can be explained by a mechanical obstruction in the beam line. In a 9 T magnetic field a larger envelope of β particles can be focussed onto the PIN diode. A corrected distribution – assuming that the centres of the distribution are at the same position – is also shown in the figure.

Since this first test was promising, a permanent structure was designed. This structure consists of a PIN diode array consisting of 8 PIN diodes arranged around an 8 mm diameter electrode (see Fig. 4.7). The structure is placed on the VB DIAG03 feedthrough (see Fig. 2.3) replacing a Faraday cup that had previously been installed there. The stray magnetic field at that position is $\sim 0.05\text{ T}$ when the lower magnet is powered to 9 T. For normalisation purposes, the count rates also have to be interpreted with respect to the amount of detected recoil ions. For the PIN diode array – containing 8 PIN diodes with their centres 15–22 mm away from the symmetry axis – average count rates of 780 events/s (2350 events/s) are expected for the complete detector array in the stray field of 6 T (9 T) applied in the trap region. A count rate of 1000 β 's/s corresponds to a combined detection efficiency and solid angle of about 1 %. During an ^{35}Ar measurement, only 10 % of the recoil ions will have a charge of 1^+ , and only half of those will contribute to the energy spectrum – due to the solid angle. This is 5 % of detected recoil ions to 1 % of detected β 's in favour of the ion count. For a measurement of the beta-neutrino angular correlation, the region in the upper half of the spectrum is more important, as this contains only one charge state. This region has fewer counts – because it is close to the endpoint –, so that the ratio of recoil ions to β 's on the normalisation detector is more or less the same. In this case the normalisation will increase the statistical uncertainty with a factor $\sqrt{2}$. But it is clear that a measurement with a 9 T field is much more favourable compared to a measurement in 6 T field.

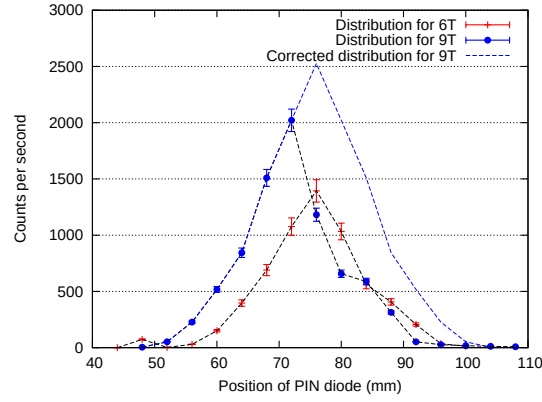


Figure 4.8 – Distribution of β 's from a ^{90}Sr source in the decay trap, in a 6 T and in a 9 T magnetic field measured by a single PIN diode. The fact that the two distributions do not have the same average position is probably due to a mechanical obstruction. A possible distribution for 9 T is also shown in the figure. The centres of the distributions lie at 76 mm.

The next step in the commissioning was to check the transmission through the electrode with a diameter of 8 mm (compared to its normal size of ~ 60 mm). Whereas during some tests a transmission of 50 % could be obtained when changing from VBEINZ01 to the PIN diode array, this was, however, not always reproduced. Because the electrode in the PIN diode array is more narrow with respect to the normal VBEINZ01 electrode, the transmission is much more sensitive to deviations of the ion beam from the axis. This will be optimised in the future.

4.2.4 Optimisation of the Penning traps

Since the traps are used to prepare the ion cloud and contain the radioactive source of the experiment, a lot of work has been put into their optimisation. Many steps can be taken in the full optimisation of the traps. Some important examples were selected here. A more detailed overview will be given in Ref. [Van Gorp, 2011].

RF Excitations

Several rf excitation schemes can be performed at WITCH. Three of these are commonly used;

- A dipolar excitation at ν_- . This moves all ions to a larger radius around the centre of the trap.
- A dipolar excitation at ν_+ . This moves only ions with a given mass away from the centre of the trap.

- A quadrupolar excitation at ν_c . This excitation – in combination with buffer gas – centres ions with a given mass.

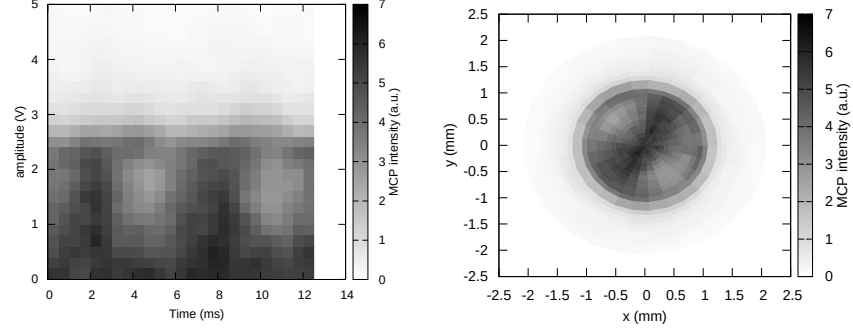


Figure 4.9 – Figure of the shape of the ion cloud in the cooler trap, realised by performing a phase-locked magnetron excitation at 171 Hz of 50 ms. Phase-locked refers to the fact that the phase of the excitation is always the same at the start of the excitation. On the **left** the raw data is shown; an intensity plot with the phase of the ion cloud motion shown on the x-axis – where the full range of the x-axis corresponds to a range of 360° – and the amplitude for the magnetron excitation on the y-axis. On the **right** this has been converted in a two-dimensional image of the ion cloud. Note that this is not necessarily the shape of an ion cloud ‘at rest’, but it is probably influenced by the excitation itself.

During a measurement without any beam contamination only a quadrupolar excitation is used in order to centre the ion cloud and reduce its radius. However, during setting up it is useful to do other types of excitations to see if the traps are operating correctly and to infer the properties of the ion cloud. The most common way to do this is by combining different excitations and scanning one parameter – i.e. the amplitude, frequency or starting phase of the excitation.

- By scanning the amplitude of a dipolar ν_- excitation one can measure the radial size of the ion cloud in the cooler trap. The pumping diaphragm prevents ions on a too large radius from being transferred to the decay trap. If one starts the excitation at a fixed phase, also the radial shape of the ion cloud can be measured. An example of this is shown in figure 4.9.
- A frequency scan of the quadrupolar ν_c frequency is used for the identification of the ion species in the trap. Also the magnetic field can be determined if this ν_c scan is performed on a (stable) ion species with a known mass (for an application of this, see section 6.3.2). To do this frequency scan, the ion cloud must first be brought to a larger radius via

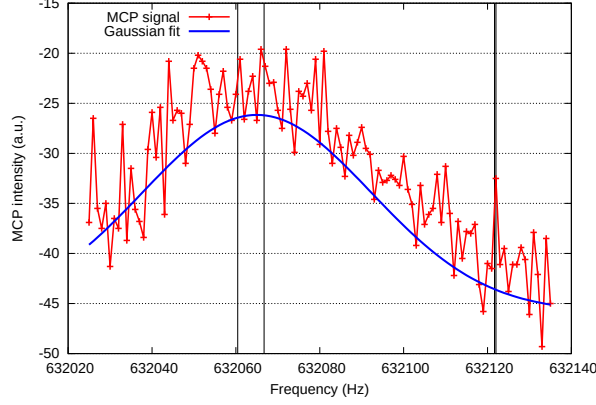


Figure 4.10 – A dipolar ν_+ frequency scan to separate different isotopes in the mass 146 isobar. A higher MCP intensity corresponds to a more negative signal. The excitation amplitude is 0.04 V and the excitation time is 4 s. Lower excitation amplitudes in combination with longer excitation times lead to a better mass resolving power. The blue (solid) line is a fit of the data with a Gaussian distribution. The central frequency of the fit is 632065 Hz, with a standard deviation of 39 Hz which corresponds to a mass resolving power of $m/\Delta m \sim 6900$. The vertical lines indicate at which frequencies responses for different isotopes from the mass 146 isobar are expected.

a dipolar ν_- excitation and afterwards the ion cloud is mass-selectively re-centred with a quadrupolar excitation at ν_c .

- A dipolar excitation at ν_+ is supposed to have a better mass resolving power (see Ref. [Coeck, 2007]). This was attempted during the beamtime of July 2010 at mass 146. As can be seen in figure 4.10, this first attempt was not successful as the width of the resonance is too wide due to the large number of ions in the ion cloud and the presence of several different isotopes.

Items which have not been tested yet, but which might provide valuable information, are;

- Performing a quadrupolar excitation in the decay trap to see by how much the magnetic field strength there differs from the cooler trap. This will not centre the ion cloud – because there is no buffer gas in the decay trap –, but it can add kinetic energy. This additional energy will modify the time-of-flight of the ion cloud towards the detector. Mass measurements of short-lived nuclei are based on this principle [Blaum, 2006].
- In a dipolar ν_+ excitation one expels ions from the centre of the trap based on their mass. Combining several frequencies by using a Fourier

transform allows to expel several masses at the same time. Performing the same excitation not at a limited number of frequencies, but over a certain frequency range, is called the SWIFT (Stored Waveform Inverse Fourier Transform) technique, see Ref. [Guan & Marshall, 1996].

- To obtain a better determination of the magnetic field using the same excitation time, one can perform a Ramsey-type quadrupolar ν_c excitation [George et al., 2007]. Instead of applying the excitation continuously for a certain time, one switches the excitation frequency on and off during this time. Applying a Ramsey-type excitation at WITCH would be cumbersome with the Gate and Delay Unit, but with the newly installed FPGA card it is fairly straightforward.

Energy optimisation

For a successful transfer of the ions from the cooler trap into the decay trap, the potentials and timings involved need to be very well under control.

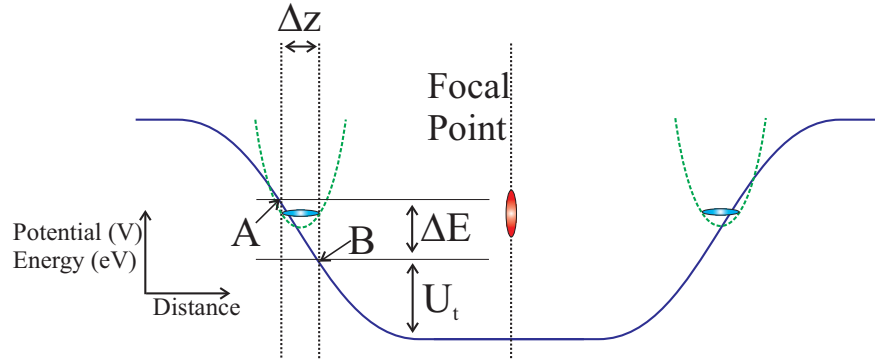


Figure 4.11 – Representation of the potentials in the cooler trap and the decay trap along the z axis. The dark blue, solid line is the potential during the transfer. The green, dashed line is the quadrupolar potential for a Penning trap. Δz is the length of the ion cloud. ΔE is the energy spread of the ion cloud after switching from the trapping potential to the transfer potential. The ion cloud (at different moments during the transfer) is represented by an ellipse.

As mentioned before, a Wiley–McLaren potential is now being used to avoid an energy increase of the ion cloud (see Fig. 4.11). The voltages during the transfer are chosen such that the centre of the quadrupolar potential stays at the same potential compared to the trapping potential, and the parabolic shape of the trapping potential is changed into a linear ramp. The main idea behind this type of potential shape is to have a focal point for the ions exactly between the centre of the cooler trap and the decay trap. Two parameters need to be under control for this: the slope of the field gradient and the potential U_t between the

two traps. A small derivation can already provide quite some insight how these two parameters influence the transfer.

ΔE is defined here as the potential difference between the axial extremities of the ion cloud, and U_t is the transfer voltage. The velocity of the ions during the transfer is then

$$\begin{aligned} v_1 &= \sqrt{\frac{2qU_t}{m}} \\ v_2 &= \sqrt{\frac{2q(U_t + \Delta E)}{m}} \end{aligned} \quad (4.5)$$

where v_1 is the speed of the ions at position ‘B’, and v_2 the speed of the ions at position ‘A’. ΔE is defined by the properties of the ion cloud itself (i.e. the length of the ion cloud, Δz) and the exact shape of the potentials when changing from the trapping to the transfer potential. In principle ΔE can be measured by doing energy scans, and Δz can then be deduced with knowledge of the potentials and the ion cloud’s energy distribution. Note that only the axial properties of the ion cloud are considered here; the radial properties do not play a role in the transfer to first order.

To have a focal point in the centre of the two traps, the ions from the two locations – ‘A’ and ‘B’ - must arrive in the centre at the same time;

$$\frac{D}{v_1} = \frac{D + \Delta z}{v_2} \Rightarrow \frac{D}{\sqrt{U_t}} = \frac{D + \Delta z}{\sqrt{U_t + \Delta E}} \quad , \quad (4.6)$$

with D the distance between ‘B’ and the centre between the two traps. From this derivation an expression for U_t can be derived;

$$U_t = \frac{\Delta E \cdot D^2}{(D + \Delta z)^2 - D^2} = \frac{\Delta E \cdot D^2}{\Delta z^2 + 2\Delta z \cdot D} \quad (4.7)$$

In a realistic situation one can have; $\Delta z = 1$ cm, $\Delta E = 1.789$ V, $D = 116.5$ mm, the endcap electrodes at 10 V during trapping and the electrodes around the central (ring) electrode at 5 V and -5 V during the transfer. The resulting transfer potential to be used is then $U_t = 9.9927$ V, which in turns leads to a total transfer time of $31.5 \mu\text{s}$. Of course, this is a first approximation; in a more detailed analysis one should also look at what happens with the ions that are within the ion cloud (and not just at the axial extremities) and the travelling time should be calculated more accurately with numerical integration methods. But already similar values were observed when working with the traps; e.g. figure 4.12 shows that a capture time – the time when the potential in the decay trap is restored to its normal trapping potential after the start of the transfer – of $32\text{--}35 \mu\text{s}$ was used with a transfer potential of -15 V, which does not correspond to U_t in Fig. 4.11, but is defined with respect to the bottom of the quadrupole trapping potential.

When the ions arrive in the decay trap it can be closed again; the timing of this is crucial. The effect of the capture time is shown in figure 4.12. It can be seen that the energy of the ions is higher if the trap is closed at the wrong

time, or the ions can be lost altogether. During the run of July 2010, endcap electrode voltages of the decay trap as low as 0.5 V were used. An example of scans to determine the energy of the ion cloud are given in figure 6.11. The figure shows a measurement of the energy of the ion cloud in the cooler trap and in the decay trap – after the transfer. Assuming that the energy of the ions follows a Maxwell-Boltzmann energy distribution, the energy of the ions in the first trap is 0.070(8) eV and 0.44(6) eV in the second trap. The energies are however also slightly shifted; 0.14(1) eV in the first case and $-0.12(6)$ eV in the latter. Additionally this measurement shows that the energy of the ions does follow a Maxwell-Boltzmann energy distribution, as has been verified by simulations as well [Van Gorp, 2010].

The main aim of further investigations of the energy distribution is twofold. Firstly, the energy gain during the transfer has to be decreased further. Secondly, it has to be measured how reproducible and stable these results are, e.g. whether the capture time or the energy of the ions change significantly with a different number of ions in the trap, with different masses, etc. An additional complication is that the energy distribution of the ions cannot be measured directly. Indeed, to eject the ions the potentials in the decay trap need to be modified and this invariably changes the energy distribution of the ions. Also the potential energy of the ion cloud (see section 6.1.1) will be converted into kinetic energy. Simulations are needed to compensate for these energy shifts.

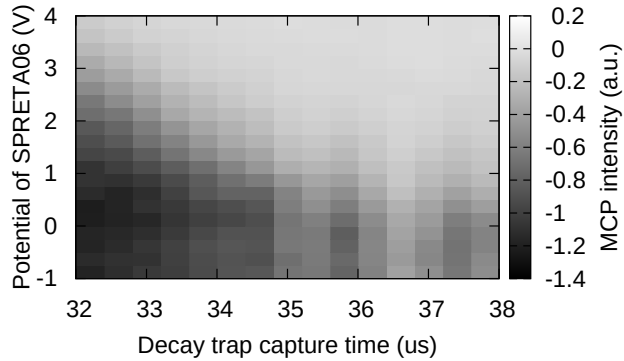


Figure 4.12 – Intensity plot of the energy of the ions on the y-axis (measured by the retardation spectrometer) versus the capture time of the decay trap. A lower value for the intensity (i.e. darker) corresponds to a larger MCP signal. At a capture time of, for instance, $34 \mu\text{s}$ one can see that the maximum energy of the ions is lower than with a capture time of $32 \mu\text{s}$.

4.3 Independence from REXTRAP

The WITCH setup relies on REXTRAP to bunch the continuous beam from ISOLDE. As such it is located relatively close to REXTRAP and the REX-ISOLDE setup. The WITCH magnets can be turned on or off. When on, they cause an interfering magnetic stray field in the beamlines of the REX-ISOLDE facility. As a consequence, over the past years the WITCH magnets could not be used during REX preparations or beamtimes. This significantly limited the amount of time available to WITCH for tests and optimisations with stable beams, which has seriously delayed the commissioning of the setup. To be independent of REX two actions were taken. Firstly, a radiofrequency quadrupole (RFQ) buncher was developed to provide, in combination with the ion source in the horizontal beamline, a bunched beam independent of REXTRAP. Secondly a magnetic shield was developed and installed around the REX mass separator, so as to eliminate the negative effects of the WITCH stray field on beams in the REX-ISOLDE facility.

4.3.1 RFQ Buncher

An RFQ was developed to bunch the ions coming from the surface ionisation source present on top of the horizontal beamline. The RFQ's purpose is to provide a bunched beam of stable ions to WITCH, preferably with beam properties – emittance, time-length, etc. – similar to what REXTRAP provides. This allows to test every aspect of the system starting from the operation of the pulsed drift tube up to the optimisation of the traps. The only aspect of the WITCH operation that cannot be fully optimised like this, is the tune of the beam itself, as this depends on the exact tune used for the beam coming from REXTRAP.

The construction and commissioning of the RFQ has been reported in detail in Ref. [Traykov, 2011]. Here some details will be highlighted. The implementation of the RFQ at the position of the already existing surface ionisation source is shown in figure 4.13.

The main disadvantage of the surface ionisation source by itself was the low intensity of the bunches that could originally be obtained with it. Indeed, although it can deliver a continuous beam with a rather high yield of $\sim 10^8$ ions/s, only the part that can be pulsed down by the PDT was useful for trapping. This is merely $4\ \mu\text{s}$ in one second corresponding to only 400 ions/bunch out of an initial 10^8 ions/s. The RFQ solves this issue as can be seen in figure 4.14. The yield is highest at low extraction frequencies, which is favourable for trapping tests. Furthermore, the beam tuning of the not yet pulsed-down beam (with a kinetic energy of 30 kV) can be easily performed with an electrometer at high extraction frequencies.

In figure 4.15 it can be seen that the time structure of the ion bunches from the RFQ nicely matches the requirements of the PDT; extraction times up to $20\ \mu\text{s}$ yield a pulse length of $\leq 4\ \mu\text{s}$.

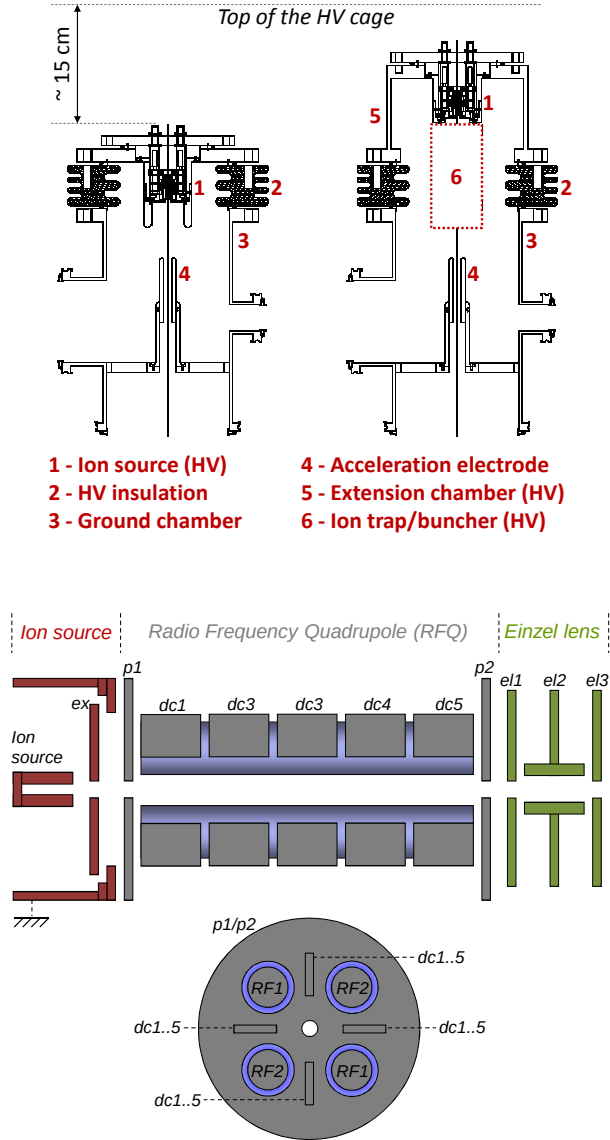


Figure 4.13 – Top: Schematic drawing of the original ion source chamber to the left, and how it was extended to accommodate the RFQ on the right. **Bottom:** Overview of the important components of the RFQ. dc1..5 are the electrodes that create the DC potential for the generation of bunches. RF1 and RF2 generate the RF field with a phase difference of π radians. el1..3 are focussing electrodes. p1 is the entrance plate of the RFQ and p2 the extraction plate. Taken from [Traykov, 2011].

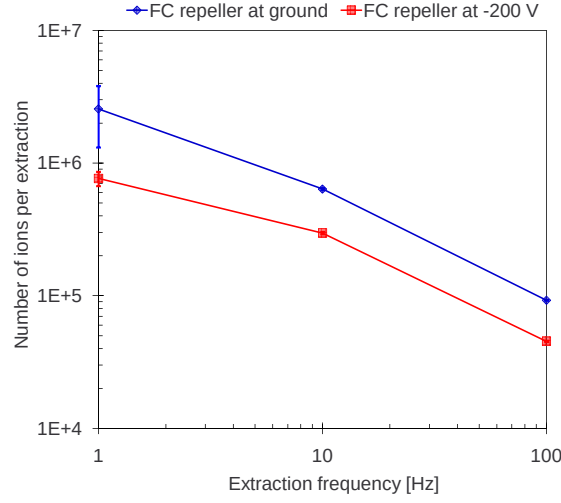


Figure 4.14 – Intensity of the ion bunches coming from the RFQ at different extraction frequencies. Taken from [Traykov, 2011].

4.3.2 Magnetic Shielding

The stray magnetic field of WITCH is unfortunately sufficiently strong to disturb other experiments. It can disturb the beam transport of the REX-ISOLDE beamline which passes close to WITCH, but it can also cause a shift in resonance frequencies at ISOLTRAP which is located somewhat further. The latter is only a problem when the magnetic field is changing. The former prevents WITCH and REX-ISOLDE to run simultaneously. This is a significant problem as the REX-ISOLDE facility is used by many experiments at ISOLDE (30–50 % of the beam time). Since a lot of tests and measurements are required to improve the efficiency of the WITCH setup and to characterise systematic effects, a solution for this had to be found. Obviously, the magnetic stray field of WITCH at the site of the REX-ISOLDE beamline had to be reduced; several options were considered to this end.

Choice of material

First of all, a good shielding material had to be selected before the shape and implementation of the magnetic shield could be designed. The equation that characterises the problem is the following;

$$\mathbf{B} = \mu_0 \mu_r(\mathbf{B}) \mathbf{H} \quad , \quad (4.8)$$

where B is the magnetic flux density (or magnetic field), H is the magnetic field intensity (or magnetising field), μ_0 is the permeability of vacuum and μ_r is the relative permeability of a specific material. The latter is a function of the

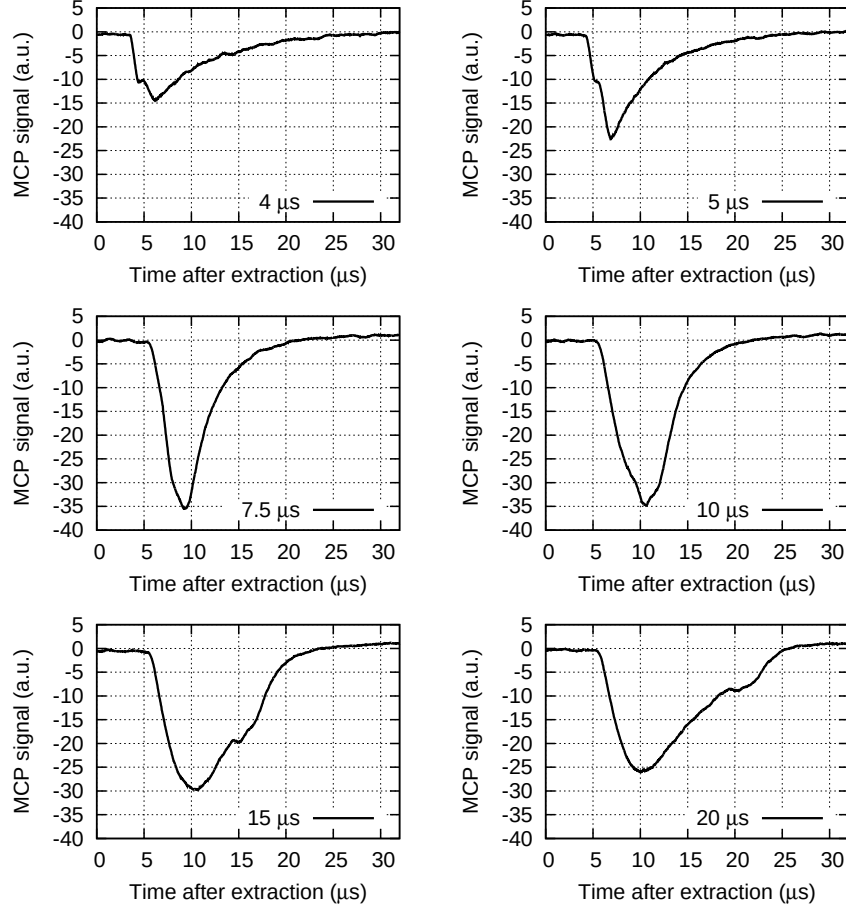


Figure 4.15 – Signals from the extracted ion bunches measured by an MCP detector (a more negative signal is a more intense MCP signal), for different extraction times (4–20 μs) and for an extraction frequency of 1 Hz. These data were taken using a high-resistive termination in the data-acquisition (see section A.3.3), effectively smearing out the timing information. The pulse length (or duration) is the part of the signal with the negative slope. A signal pick-up from the switching is present in all spectra; it can be seen at the time of the closing of the RFQ buncher (e.g. for an extraction time of $x \mu\text{s}$ it is present at $x \mu\text{s}$). Pulse length of the order of 2–4 μs are required for efficient operation of the pulsed drift tube. Modified from [Traykov, 2011].

magnetic field. B in Eq. 4.8 is the magnetic field generated by a ferromagnet in response to a magnetic field intensity. The magnetic field intensity, H , can be generated by a solenoid. A hand-waving way to explain the functioning of a magnetic shield is to say that the higher the μ_r of a certain material, the higher the magnetic flux density B in the material will be. This will reduce the magnetic field intensity behind the shield, as the magnetic field lines will be ‘compressed’ inside the shield. This follows from Gauss’s law for magnetism.

In figure 4.16 $\mu_r(B)$ for iron and mumetal is shown as a function of the magnetic field intensity. The main difference between these two materials is the saturation point and the value of μ_r . In low magnetising fields mumetal already has a very high permeability compared to iron, allowing it to provide good shielding. However, the permeability quickly saturates, which means that in high fields μ_r will go to unity and provide no additional shielding. For iron the conclusion is the opposite; its shielding properties are intrinsically not that high, but it can still provide efficient shielding in higher fields. Further, an iron shield close to the WITCH setup would exert a huge force on the magnets. This could especially be a problem at WITCH since the magnets are not always turned on and the ratio between the two fields is not constant. All this led us to choose a mumetal shield installed around the REX beamline instead of an iron shield around the WITCH setup itself. This was discussed with the scientific and technical staff responsible for the REX-ISOLDE setup.

Implementation

In a first phase only the beamline between the REXEBIS charge breeder and the vertical beamline of the REX-ISOLDE mass separator was shielded. This part was deemed to be most influenced by the WITCH stray field. Detailed simulations were done with COMSOL [com, 2010] to estimate the effect of imperfections in the shield (i.e. holes through which the stray field can penetrate). A reduction of the stray field by a factor – or a so-called shielding factor – of 10 was easily obtained with the shield. With iron this would not have been possible; a maximum shielding factor of 5 was estimated before starting detailed simulations. A mumetal magnetic shield for the first part of the REX beamline was subsequently developed (see Fig. 4.17).

In a second phase also the bottom part of the REX mass separator was outfitted with a mumetal shield (Fig. 4.18). This ensures that the full separator is shielded and avoids an asymmetrical situation by having only part of the separator shielded.

Measurements and Results

The requirements for the shielding are constrained by the typical operation of REX-ISOLDE [Habs et al., 2000]. Ion bunches from REXTRAP enter the REXEBIS charge breeder with a kinetic energy of 30 keV. When they leave REXEBIS they have an energy of 5 keV per nucleon. The ion bunch goes through a separator similar to a Nier-spectrometer [Nier & Roberts, 1951]. This

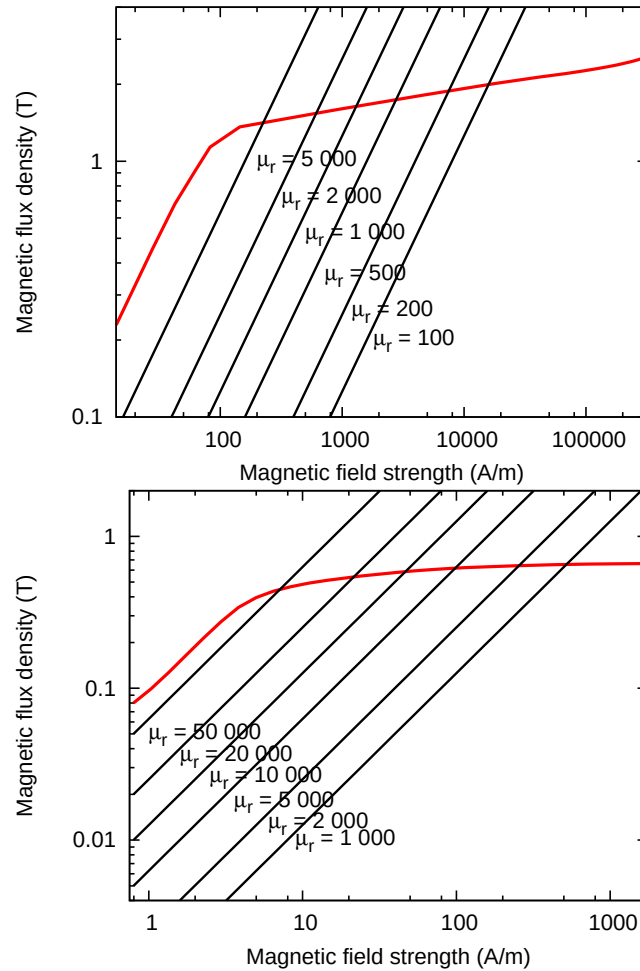


Figure 4.16 – At the **top**, the relative magnetic permeability of iron and at the **bottom**, μ_r of mumetal in function of the magnetic field strength are shown. The curve in red is the magnetisation curve (or part of a hysteresis curve) and is a property of a sample from the material. The parallel lines denote lines with a constant magnetic permeability μ_r and are there to interpret the graph more easily. The hysteresis curve depends heavily on the exact type of material and how the material was treated. A magnetic stray field of 1 G ($=0.0001$ T) corresponds to about 80 A/m in vacuum.

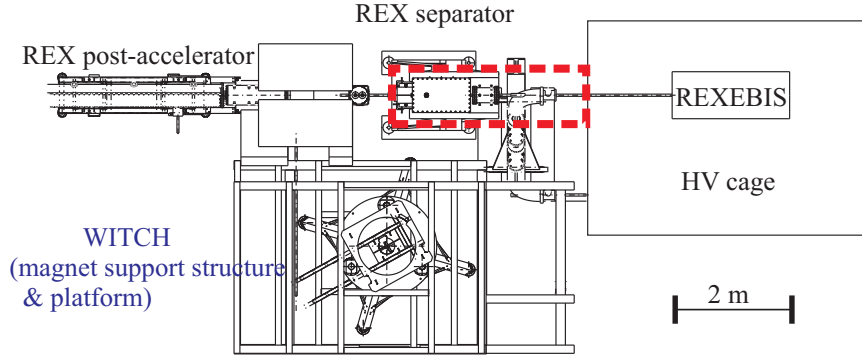


Figure 4.17 – Top view of the installation of the WITCH and REX setups. The first (top) part of the magnetic shield is indicated with a red dotted line.

is to avoid transmission of charge bred contamination from REXEBIS into the post-accelerator. The separator consists of both an electrostatic and a magnetic bender. For a radioactive run – with typically a beam of very low intensity – the system is first tuned with a so-called pilot beam – with a much higher intensity; this is chosen such that it has an A/q ratio close to the A/q ratio of the intended radioactive beam, with A being the number of nucleons and q the electric charge of the ions expressed in units of elementary charge. When switching to the radioactive beam, the fields on the beam optic elements have to be scaled according to the change in the A/q ratio to retain the same transmission efficiency of the beam.

This procedure works fine as long as the WITCH magnets are not turned on as the stray field disturbs the beam tune of REX-ISOLDE. It is possible, however, to compensate for this by retuning, but then also the A/q scaling needs to be preserved. The latter is the trickiest part. First beam tests to quantify the effect of the WITCH stray field on REX-ISOLDE were carried out in late 2007. It was shown that by ramping the lower magnet to 3 T the operation of REX was not hampered (i.e. beam tune and A/q scaling), however, when also ramping the upper magnet to 0.1 T the beam was lost and could not be regained.

The first part of the shield was then installed and the measurements repeated in late 2009. The good news was that the transmission of the beam could be recovered with fields of 4 T and 0.1 T. The bad news was that the A/q scaling was not 100 % efficient, even not with only the lower magnet turned on. The latter was in fact a less favourable result than what we obtained without any shielding. This led to the construction of the bottom part of the shielding to restore the symmetry of the shield around the separator. It was thought to be very probable that the operation of the separator was disturbed by having only one part shielded and the other not.

A final series of measurements with the two shields were performed at the end of 2010. With WITCH magnetic fields of 3 T and 0.1 T the A/q scaling in REX

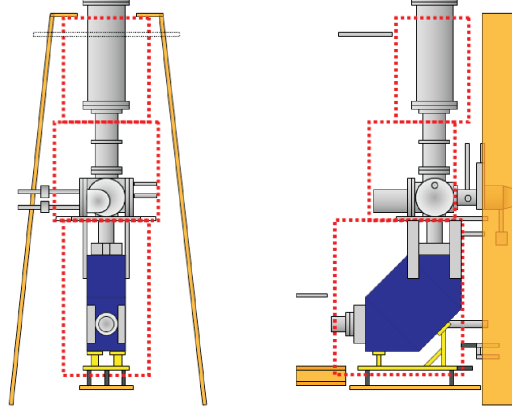


Figure 4.18 – Drawing of the lower part of the shielding around the REX beamline. The dotted lines indicate the area of the shield. The black area is the magnetic part of the REX separator. Taken from [Traykov, 2010].

was found to work perfectly. This was checked with ^{39}K ions with a charge q in the range of 11–14. This corresponds to an A/q ratio of 2.79–3.55, which is a larger range than the typical A/q scaling needed during a radioactive run. Based on these tests one can conclude that WITCH and REX-ISOLDE can now operate simultaneously for beams of $A \sim 40$ and above. Similar measurements with a ^{23}Na beam are planned to investigate whether simultaneous operation for such low-mass beams is possible too.

4.3.3 Outlook

Ions coming from the RFQ buncher have been trapped already in the WITCH Penning traps. The bunches have the required properties; they are sufficiently intense ($\sim 10^6$ ions/bunch) and have a good time structure (i.e. a length less than $4\mu\text{s}$). With the flexibility of the operation one can foresee that trap tests for different ion numbers will be easily manageable. However, a working RFQ buncher without the ability to turn on the magnets – i.e. when REX is running – is rather pointless. This problem has been solved by the installation of a magnetic shield around the REX-ISOLDE mass separator. WITCH can now in principle run with fields of 3 T and 0.1 T without disturbing the operation of REX-ISOLDE. A short retune of the REX beam – compared to the tune with the WITCH magnets off – is the only requirement. The modalities under which WITCH and REX-ISOLDE can simultaneously run are still to be discussed.

Chapter 5

Penning-like Traps at WITCH

In this chapter the focus will lie on ionisation processes that occur in the WITCH retardation spectrometer. WITCH is the first experiment that combines a Penning trap with a retardation spectrometer. This novel combination leads to new challenges, but it also has many similarities with other experiments based on a retardation spectrometer like aSPECT [Glück et al., 2005] and KATRIN [Weinheimer et al., 2002]. The particular configuration of electric and magnetic fields used in this type of spectrometer can lead to particle traps besides the cooler and decay trap, which can in turn lead to ionisation and discharges in the system. The focus will lie on particle traps which disturb a correct measurement or interpretation of recoil ion energy spectra, but also particle traps in other parts of the setup will be briefly discussed for completeness.

First of all, a general introduction will be given of how unwanted particles can be created in the setup and how they can remain trapped. Regions of unwanted particle traps in the WITCH spectrometer are then identified. Secondly, ionisation phenomena that have been observed in measurements are listed and are explained in terms of Penning-like traps. Thirdly, simulations were performed to explain a specific spectrum measured by changing the voltage on the einzel lens electrode. The simulations allow a further investigation of the microscopic ionisation mechanisms at play in the WITCH setup. Finally, solutions for the trapping of electrons in unwanted traps are discussed, of which one was already installed.

5.1 Ionisation Processes and Penning-like Traps

In this section ionisation processes will be discussed in general; how charged particles can be created in a setup and which are the processes that are likely to be important for the WITCH setup. Then Penning-like traps that can be formed

due to specific electromagnetic field configurations are discussed and how they can influence measurements. The ionisation processes create charged particles that can be multiplied in Penning-like traps; doing so they contribute to the background count rate and can disturb the measurement of a recoil ion energy spectrum significantly. Finally, Penning-like traps that exist in the WITCH setup are identified.

5.1.1 Ionisation Processes

In a setup where strong electric fields and radiation are present, several ionisation processes – i.e. the creation of electrons or ions – on the surface of electrodes can occur. In general one can distinguish between two major primary ionisation processes;

- Ionisation by particle collisions. This item covers a whole range of processes. Electrons can be emitted from materials by the photoelectric effect, Compton scattering or pair creation due to interactions with photons (γ radiation). Also ions can be ejected from materials by electron sputtering (β radiation) or ion sputtering. Molecules and atoms can be desorbed from the vacuum walls when they receive sufficient energy. Muons created by cosmic background radiation can release electrons from the inner vacuum walls or electrode surfaces. Electrons already present in the setup can ionise rest gas atoms and create an extra electron in the process (see Eq. 5.1).
- Field emission from an electrode surface. Sharp tips or edges on the surface of an electrode will create high electric field gradients which can cause the emission of particles. Most important is to have smooth surfaces for cathode-type electrodes, to avoid field emission of electrons. The smoothness of the anode-type electrode surfaces is less critical, as field emission of ions is harder to achieve.

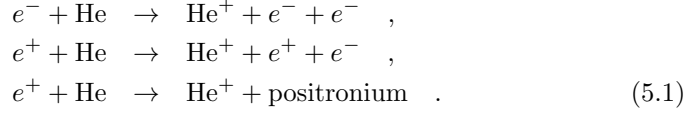
When a magnetic field line connects two electrodes with a large voltage difference, this can lead to an amplification process. Electrons will accelerate towards the electrode on the most positive potential, where they can create ions on the surface, or from the rest gas. These ions will then be accelerated towards the most negative potential, where they can create electrons. This continues until a major discharge occurs and the power supplies providing the voltages for the electrodes trip.

However, a primary ionisation event is not problematic by itself. Field emission electrons can be easily absorbed by another electrode. If the potential of this other electrode is not too different from the initial electrode, this will not cause further ionisation. The same is true for ionisation by particle collisions; if there is no amplification mechanism, the ionised particles will be absorbed by the electrodes or the walls of the vacuum chamber.

But reality is often different; ions or electrons created in the system are likely to cause further ionisation processes. The rest gas at WITCH consists mainly of

atoms and molecules found in the atmosphere; e.g. O₂, N₂, CO, H₂O, etc. During an experiment, however, the rest gas in the spectrometer will mainly consist of helium which is used as buffer gas in the cooler trap. For the following discussion the focus will thus lie on helium.

Helium can be ionised by electrons or positrons (β^+) via several processes;



Cross sections for the first process are given, up to low electron energies, in Ref. [Shah et al., 1988] and are shown in figure 5.1. The last two processes are described in Ref. [Fromme et al., 1986]. Cross sections for ionisation of atoms by low-energy singly-charged ions have not received a lot of attention in literature; often the ionisation is studied with higher-energy ($\mathcal{O}(\text{keV})$) multiply-charged ions. The reported cross sections (see e.g. Ref. [Crothers & McCann, 1983]) are negligible compared to ionisation by electron impact. The reason for this is that ionisation does not depend on the energy of the impinging particle, but on its velocity, which is much larger for electrons than for ions of the same energy. Ionisation by ion impact will thus not be considered anymore. The probability for an electron to ionise a helium atom is given by

$$P_{\text{ion}} = \sigma_{\text{ion}} \cdot n \cdot l = \frac{\sigma_{\text{ion}} \cdot p \cdot l}{k_B \cdot T} \quad , \quad (5.2)$$

with P_{ion} and σ_{ion} the ionisation probability and cross section, respectively, the density of the (helium) gas n , the path length of the electrons l , the partial pressure of helium p , the temperature of the rest gas T and the Boltzmann constant k_B . When $P_{\text{ion}} > 1$ this formula does not describe a probability anymore, but rather a yield. Using $p = 1.0 \cdot 10^{-7}$ mbar, $T = 293$ K, $\sigma_{\text{ion}} = 0.604 \cdot 10^{-17} \text{ cm}^2$ – which is the case for 29.6 eV electrons impinging on helium atoms (see figure 5.1) –, an ionisation probability P_{ion} of $1.5 \cdot 10^{-6}$ per metre of electron path length is obtained. This is negligible if an electron traverses the system and is then lost. However, if an electron is trapped somewhere in the system the probability for one electron to create an ion is unity. For an electron with a constant kinetic energy of 29.6 eV this is realised within ~ 0.2 s.

5.1.2 Penning-like Particle Traps

In a Penning trap setup high magnetic fields and electric fields are required to have well-defined trapping regions. A so-called MAC-E filter retardation spectrometer [Picard et al., 1992] also requires magnetic fields and high electric fields. On top of the well-defined trapping regions, Penning-like traps can be formed at undesirable locations due to the combination of magnetic and electric fields. These unwanted particle traps will be referred to as Penning-like traps, since they usually do not have the quadrupole electric field of an ideal Penning trap or a homogenous magnetic dipole field. Moreover referring to them as

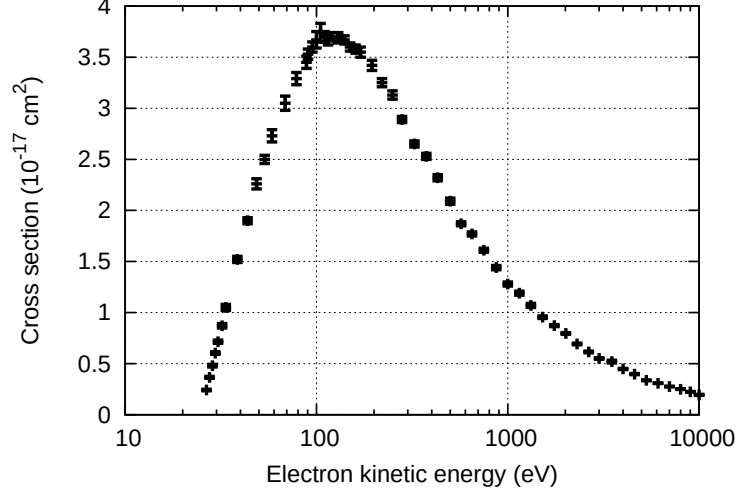


Figure 5.1 – The cross section for ionisation of a helium atom by impact of an electron. Created from data in Ref. [Shah et al., 1988].

Penning-like traps allows a clear distinction from the wanted Penning traps; i.e. the cooler trap and the decay trap. An unwanted trap is relatively easy to form; two ‘endcaps’ connected by a magnetic field line are sufficient. An endcap can be formed by a region with a higher positive (negative) potential – with respect to its surroundings – for positive ions (electrons), but also by an electrode or by a magnetic mirror, i.e. a transition region from a low to a high magnetic field. Unless this is continuously kept in mind during the design phase of an experiment, unwanted traps are almost unavoidable. However, this does not mean they will pose a problem for the experiment, as particles will have to enter an unwanted trapping region and stay trapped there to cause visible effects.

Depending on the experimental conditions the electrons in an unwanted Penning-like trap can cause charge amplification, a self-sustained discharge or a runaway discharge. Charge amplification will cause one electron to create several other ion–electron pairs. This process dies out when the source of the primary electrons is taken away or is reduced. In a self-sustained discharge this is not the case; even when the source of the primary electrons is taken away, a self-sustained discharge will keep creating ion–electron pairs. This can be achieved for an electron trap; as long as each electron creates one ion–electron pair without losing energy, the discharge will be self-sustained. If one electron creates many other ion–electron pairs, one can speak about a runaway discharge. The amount of electrons in the Penning-like trap will keep on increasing and eventually the current of particles leaking from an unwanted trap by such a discharge process will cause power supplies of electrodes and detectors to break down. Note that the processes described here are not unlike the criticality k

of a nuclear reactor, with k being the number of secondary electrons created by a primary electron if no energy is lost. If $k \ll 1$ no ionisation from the unwanted trap will be seen. If $k < 1$, one merely has charge amplification. If $k \approx 1$ the unwanted trap will be self-sustained, and finally, if $k > 1$ one has a runaway discharge. It should be noted, though, that an unwanted trap is subject to stochastic processes and thus a trap can go from being supercritical to subcritical, or the other way around.

Whether a discharge in a trap is self-sustained or not depends on the rate of electrons entering the trap via primary ionisation events, on the creation of new electrons via secondary ionisation events and on the rate of electrons leaking out of the trap. Compared to ions, electrons can rather quickly lose their energy via synchrotron radiation due to their cyclotron motion, via collisions with the rest gas and via ionisation of atoms. Most of the synchrotron radiation will come from the cyclotron motion and not from the axial motion, because $\omega_c \gg \omega_z$. However, the longitudinal motion can be converted into transversal motion by atom/ion–electron collisions and thus be lowered by synchrotron radiation. The kinetic energy will also be reduced due to ionisation of atoms. Once the energy and the speed of the electron is too low – i.e. lower than the electron binding energy in an atom, which is 24.6 eV for helium – it will not cause any further ionisation.

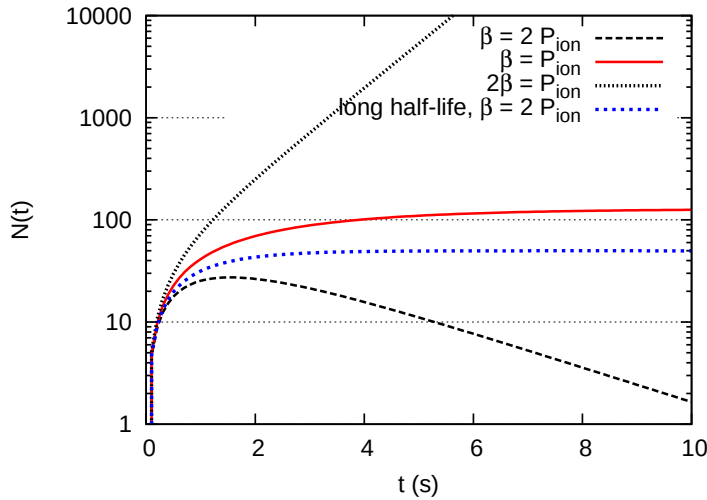


Figure 5.2 – Examples of the evolution of the number of electrons ($N(t)$) in an unwanted trap in which the primary ionisation processes are caused by radiation (three graphs are an example for ^{35}Ar decay with a half-life of 1.7752 s and one graph for a half-life 1000 times longer). When the probability of an electron leaving the trap is equal to the probability of creating a new electron, the number of electrons remains constant after a while.

One can model the evolution of a Penning-like trap as follows;

$$\frac{\partial N}{\partial t} = \alpha - \beta N + P_{\text{ion}} N \quad , \quad (5.3)$$

where N is the number of electrons in the trap, α is the accumulation of electrons by primary ionisation events, $-\beta N$ is the loss of electrons which also depends on the amount of electrons in the trap and P_{ion} is the ionisation cross section by electron impact as in equation 5.2. The term α can be due to field emission of electrons, but it can also be correlated to radioactive decay which will give it the form

$$\alpha = \alpha_0 \cdot N_{\text{PT}} \cdot e^{-\ln 2 \cdot t/t_{1/2}} + \alpha_{\text{field}} \quad . \quad (5.4)$$

This last equation includes the probability α_0 that an electron will be created by the radiation from radioactive decay, the number of radioactive ions N_{PT} in the source and a coefficient α_{field} to take field emission into account. For long half-lives the effect of radiation from decay plays a similar role as accumulation of electrons due to field emission; the influx of electrons from primary ionisation events is constant in time. The last term in equation 5.3, $P_{\text{ion}} N$, is another growth term which describes the creation of ion–electron pairs by electron impact. The most difficult term to describe correctly in equation 5.3 is $-\beta N$, i.e. the loss of electrons from the trap. This will depend on the initial energy the electrons have, on how much energy they lose due to synchrotron radiation and on the binding energy of the rest gas atoms. A trapped electron with a maximum initial energy of 100 eV will only be able to ionise 4 helium atoms, with an electron binding energy 24.6 eV, at most. After those 4 ionisation events, and provided it does not gain energy, it will be irrelevant for the ionisation of helium atoms and at some point it will physically leave the trap because it is not trapped by the magnetic field lines anymore. The evolution of the number of electrons, $N(t)$, in an unwanted trap in which the primary ionisation is caused by radiation is shown for a number of specific cases in figure 5.2. Several of these cases have been observed at WITCH under different circumstances.

To summarise, an unwanted Penning trap can express itself in the following ways.

- If the trap maintains a self-sustained discharge or a runaway discharge, it can cause tripping of electrodes or detectors. This was the reason for the construction of the compensation magnet (see section 4.2.2).
- Instead of causing discharges, the particles in an unwanted trap can simply maintain themselves without causing considerable extra background count rates. This can, however, disturb the path of recoil ions through the spectrometer by modifying the potential.
- Particles in an unwanted trap can ionise rest gas which does not remain trapped; e.g. electrons in an unwanted trap creating ions. The ions will not be trapped in the initial unwanted electron trap and can thus cause problems in other parts of the system; i.e. filling another unwanted trap or causing an increased background count rate on the detector. This is

especially harmful if the charge amplification caused by the particles in the trap depends on parameters that vary during an experimental cycle (e.g. the intensity of γ radiation), instead of generating random noise.

5.1.3 Penning-like Traps at WITCH

Table 5.1 – *Typical settings for the electrodes in the spectrometer. The retardation voltage (ret. voltage) typically ranges from 0 V to 500 V. The electrodes on a high negative negative potential should be set as low as possible, while the voltage of SPEINZ01 can be tuned to have better focussing of the recoil ions onto the detector.*

Electrode	Value (V)
SPRETA01	0
SPRETA02	$0.3 \times \text{ret. voltage}$
SPRETA03	$0.6 \times \text{ret. voltage}$
SPRETA04	$0.9 \times \text{ret. voltage}$
SPRETA05	$0.9 \times \text{ret. voltage}$
SPRETA06	ret. voltage
SPRETA07	ret. voltage
SPACCE01	-2000
SPACCE02	-9000
SPEINZ01	-600
SPDRIF01	-9000
SPDRIF02	-9000

The WITCH spectrometer consists of three distinct sections; the retardation section, the re-acceleration section and the detection section (Fig. 5.3). The retardation section is the energy selector of the experiment; the magnetic field changes the radial ion motion adiabatically from the trap region until it is almost completely converted into axial energy in the analysis plane in SPRETA06. In the re-acceleration section the ions that pass the retardation potential are picked off the magnetic field lines by the high negative potential of the re-acceleration electrodes and are then focussed towards the detector. In the detection section the MCP detector is floating at a high negative potential. Typical voltages for the electrodes in the spectrometer are given in table 5.1.

For the magnetic field lines in the spectrometer, see figure 2.4. Different possibilities for unwanted Penning-like traps in the WITCH spectrometer exist (see figure 5.3 as well);

- Between the decay trap and the re-acceleration section. This can be a trap for negative particles. One endcap of the trap is formed by a magnetic mirror and the other end by the high negative potential in the re-acceleration section.
- Similarly a trap for positive charges can exist between the decay trap and the (positive) retardation barrier. However, this is not a static trap and will only be present when the spectrometer electrodes are at a sufficiently

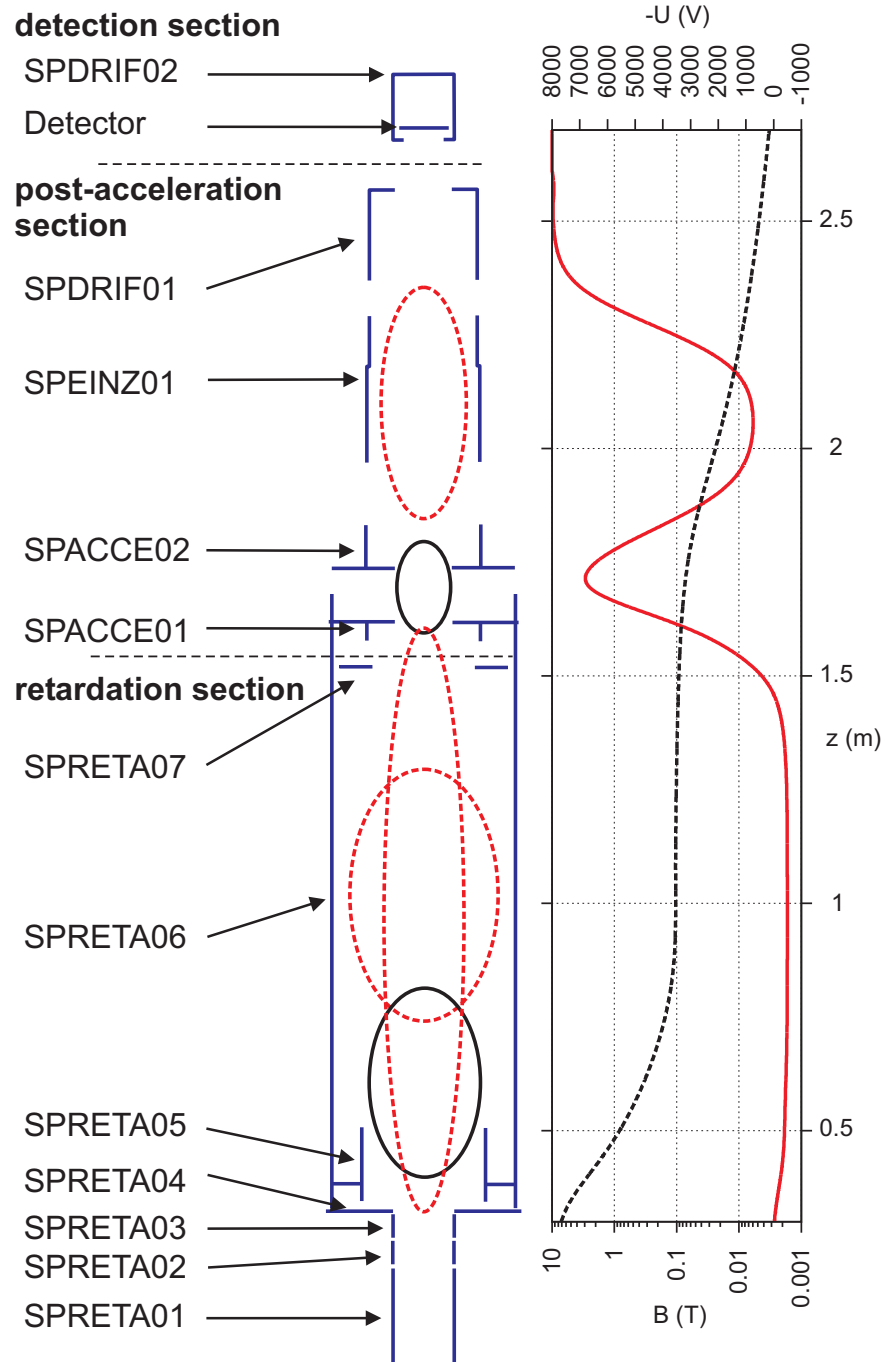


Figure 5.3 – To the left the entire retardation spectrometer is shown with its electrodes and Penning-like traps indicated in dashed red (full black) lines for negative particles (positive particles). To the right the magnetic and electric field on the central axis are shown.

high positive voltage. The exact meaning of ‘sufficiently high’ has to be determined from measurements.

- The (positive) retardation potential itself can be a trap for negative particles.

For completeness, the following positions are mentioned as well;

- In the actual Penning traps, unwanted traps can also be formed. For instance the endcap electrodes of the traps at a high positive potential can be a trap for negative particles. Also this trap is not static. Obviously, the decay trap and the cooler trap can also trap positive particles that can be different from the expected ion species during a measurement.
- Unwanted traps can exist outside of the spectrometer as well; e.g. in the vertical beamline between the negative potentials downstream of the PDT and the high magnetic field of the trap region, or between the negative potentials downstream of the PDT and the negative potentials in the re-acceleration section. The magnetic field in the VBL is rather weak however, which can render an unwanted trap in that region rather unstable.

Every unwanted Penning-like trap can be a potential source of discharges in the system. However, without the trapping of primary ionisation products and an amplification mechanism, an unwanted Penning-like trap does not pose an issue for the operation of the system. Unfortunately, some of the unwanted Penning traps did express their existence in the setup; some more violently than others.

In the next three sections harmful unwanted Penning-like traps will be identified based on measurements, simulations and tentative solutions. In the first section (section 5.2, Measurements), the acquired data will be interpreted in terms of the unwanted Penning-like traps mentioned above. In the section with simulations (section 5.3.1) it will be investigated whether one particular measured spectrum (Fig. 5.12) can be reproduced with particle tracking simulations. Also the origin of the ionisation is discussed in more detail in this section. Finally, possible solutions to remove the unwanted traps or to avoid the effects of these traps will be discussed (see section 5.4), one of which has been implemented already. Preliminary measurements will allow to evaluate this first solution.

5.2 Measurements

The investigation of ionisation in the system – caused by Penning-like traps – is not straightforward. Ionisation has been observed during radioactive beam times and during dedicated measurements, and a vast amount of – sometimes confusing – data has been taken. In this section the acquired data concerning ionisation will be presented according to the observed phenomena, and discussed in terms of Penning-like traps. First, a list of all isotopes that have been used during this investigation will be given and the conditions in which they have been measured. Secondly, the measurement cycles used will be briefly reviewed

to allow a smoother presentation of the data. Then the data is presented, along with an interpretation. Afterwards, other locations where ionisation processes occur are also mentioned for completeness. Finally, the data is summarised and the impact of the different phenomena on a measurement at WITCH is discussed.

5.2.1 Isotopes and Measurement Conditions

The data presented in this section has been gathered over a period of 3 years, both in online runs and dedicated offline measurements. The isotopes used are;

- ^{124}In (and $^{124\text{m}}\text{In}$): beamtime November 2006
- ^{116}In : beamtime November 2006
- ^{35}Ar : beamtimes October 2007 and November 2009
- ^{60}Co : offline measurements December 2006, June 2007 and July–August 2009
- ^{90}Sr : offline measurement December 2006
- ^{137}Cs : offline measurement January 2011

The decay schemes of these isotopes are given in appendix E.

Each of these sources produces different kinds of particles or radiation; i.e. γ radiation (^{124}In , $^{124\text{m}}\text{In}$, ^{60}Co , ^{137}Cs and, with a low intensity, ^{35}Ar and ^{116}In), β^- radiation (^{90}Sr , ^{124}In and $^{124\text{m}}\text{In}$), β^+ radiation with subsequent annihilation γ 's (^{35}Ar) and recoil nuclei (^{116}In , ^{124}In , $^{124\text{m}}\text{In}$ and ^{35}Ar). During online measurements the source was stored in the decay trap, while for the offline measurements the sources were mounted on a source holder and placed in the centre of the decay trap.

The intensity of the sources is also an important parameter. For $^{124}\text{In}/^{124\text{m}}\text{In}$ this was estimated to be $1.4(2) \cdot 10^5$ ions per trap load [Beck et al., 2011], with a half-life of 3.12(9) s for the ground state, ^{124}In , and 3.7(2) s for the isomeric state, $^{124\text{m}}\text{In}$. The intensity of ^{35}Ar in the two beamtimes is hard to estimate due to the absence of a clean recoil ion energy spectrum. The adopted value for the half-life of ^{35}Ar is 1.7752(10) s [Severijns et al., 2008]. The activity of the ^{90}Sr source is ~ 200 kBq. Different ^{60}Co sources were used for the various measurements; in December 2006 the activity of the source was 11 kBq and for the other measurements it was 40 kBq (both sources were calibrated in March 2007, so the half-life of ^{60}Co , i.e. 1925.28(14) days, needs to be taken into account).

Furthermore, different experimental conditions can also influence ionisation processes. Especially the vacuum level is important, as the rest gas atoms provide a ‘feeding ground’ to create ions. Also, different settings of the electrodes (and specifically the re-acceleration electrodes) influence the focus of the ions onto the detector.

Several upgrades important for the reduction of the ionisation were performed in the period of 2008–2009. Important in this respect were the improvement of the vacuum in all its aspects, the electropolishing of the re-acceleration electrodes and the implementation of the compensation magnet. The compensation magnet is present only since the ^{35}Ar run in 2009. All this is described in detail in chapter 4.

5.2.2 Measurement Cycles

Three different measurement cycles were used to obtain the data;

- Measurement of a recoil ion energy spectrum during one experimental cycle. In these measurements the retardation voltage is ramped from 0 V to a certain maximum value – high enough to stop all recoil ions – during one measurement cycle. Thereafter, the voltage on the retardation spectrometer is reset to 0 V and the next cycle started. This cycle is sometimes referred to as a retardation spectrum.
- A so-called on/off measurement. In this type of measurement the retardation voltage is switched between two extreme values; e.g. 0 V (off) and 300 V (on). This allows to see the difference between recoil ions being present in the spectrum and not, provided that the highest potential is sufficient to stop all recoil ions.
- The voltage on the retardation spectrometer can also be kept at a constant value to avoid effects that can arise due to switching of the voltages. A big difference with this method is that the voltage stays constant all the time, also between subsequent measurement/experimental cycles which is not the case for the on/off method and the retardation spectrum methods. The disadvantage of this method is that the amount of ions in the decay trap during the different measurement cycles can fluctuate.

Most measurements presented here were performed with the on/off method, some with the retardation spectrum method, and one measurement with a set of constant retardation voltages. For an offline source the measurement cycles follow each other continuously, while during a radioactive run the next measurement cycle can only be started after a new ion cloud has arrived in the decay trap; this depends on the protons impinging on the ISOLDE target which is of the order of every 5 s.

5.2.3 Observed Phenomena

A large amount of data characterising ionisation processes in the spectrometer has been taken over the years. A selection was made here to illustrate the observed properties of the ionisation processes that occur in the spectrometer. Different phenomena have been observed and will be discussed;

- The background count rate depends on the retardation potential.
- The time scales involved in the ionisation processes; often the ionisation needs some time to build up.
- Discharges that hamper a correct operation of the setup.
- Increased count rate when switching the retardation potential in large steps (of the order of 100 V or larger).
- Dependence of the ionisation processes on the einzel lens electrode voltage

Retardation-Dependent Background

The effect that is most important to have well under control for the measurement of a correct recoil ion energy spectrum, is a background that depends on the retardation voltage. If the background during the measurement of a recoil ion energy spectrum is not completely flat, one cannot deduce a correct value for the β - ν correlation coefficient a . The effect is similar to ion losses in the decay trap – when a retardation spectrum is measured during a single experimental cycle –, but systematic effects due to ion losses can be precisely characterised or even avoided, while a retardation-dependent background cannot be precisely quantified due to its stochastic nature. Such a retardation-dependent background has been observed during the ^{124}In run of 2006, the ^{60}Co measurement in 2009 and the ^{35}Ar run in 2009; it was not seen in other measurements as it was hidden in a much larger ionisation effect.

An on/off measurement from the ^{124}In run is shown in figure 5.4, top panel. The expected behaviour – fewer recoil ions at a retardation voltage of 300 V – was in fact reversed. In the first 1.25 s the retardation voltage is at 0 V, and in the last 1.25 seconds the retardation voltage is at 300 V. The peaks in the spectrum will be discussed later. The same measurement was repeated for different voltages for the ‘on period’; i.e. at 50 V, 100 V, 200 V and 300 V. The results from this are shown in figure 5.5. In the first spectrum (#1), which contains 20 measurement cycles, a clear increase correlated with the retardation voltage can be seen. This is in general true for all columns. Some small deviations are seen, e.g. for 300 V from the first to the second spectrum, but this underlines the stochastic nature of the ionisation processes. Also, for one specific retardation voltage, the number of counts is rather important when it is switched on (first spectrum) and continues at a lower rate thereafter. For 200 V for instance the first 20 spectra (#1) contain 22290 counts, while about 10000 counts are present in every next spectrum.

The fact that the increase in count rate in the first column is higher than the other columns can be an experimental artefact. Between measurements the potential in the spectrometer is left at 0 V, keeping electrons trapped in a larger electron trap between the high magnetic field and the negative potential of the re-acceleration electrodes. When the retardation potential is changed to a more positive value the electrons gain kinetic energy, whereas before their energy was not sufficient to ionise a rest gas atom. The electrons spend the largest part

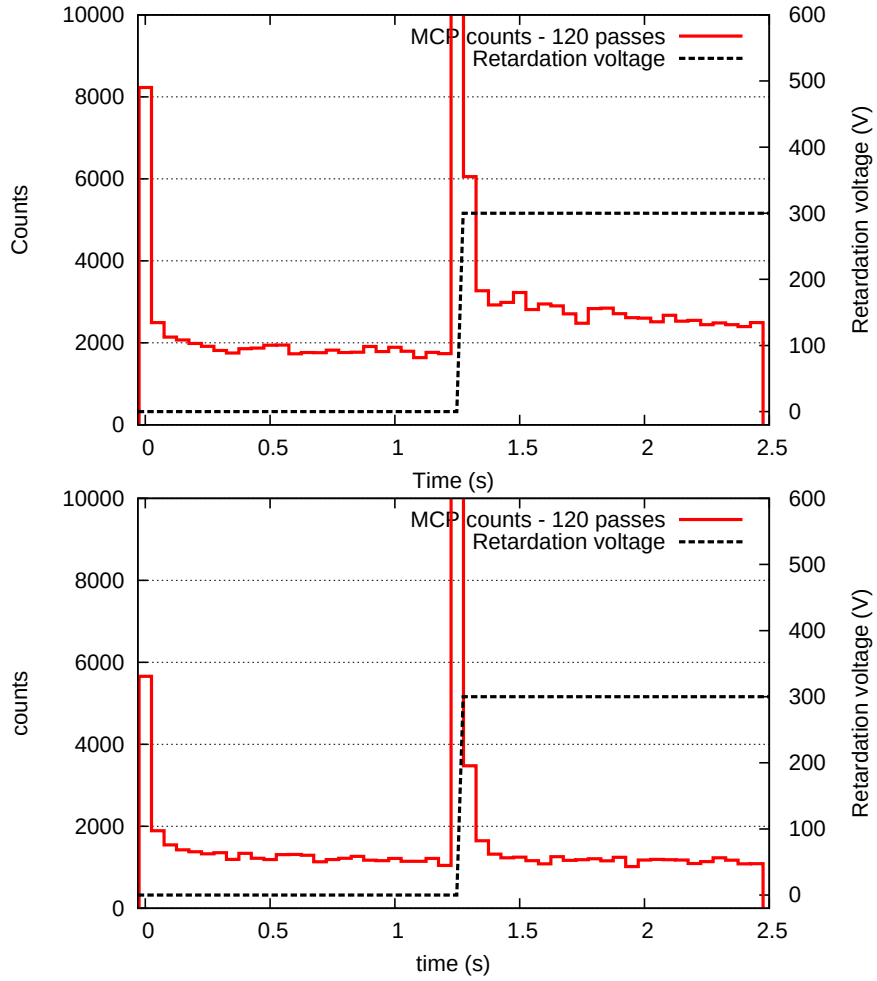


Figure 5.4 – Observation of ionisation during the ^{124}In run of 2006. The **top** panel shows an on/off measurement with 0/300 V. The **bottom** panel shows the same, but with the ions now being dumped on the pumping diaphragm in the cooler trap.

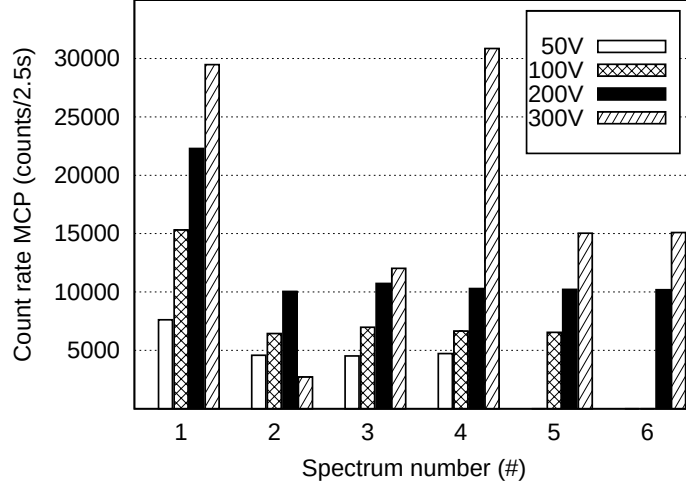


Figure 5.5 – Effect of the retardation voltage on the created ionisation. The different bars denote different spectra – each spectrum contains 20 measurement cycles. The measurements were taken like in figure 5.4 (top panel); an on/off measurement with 0 V on the retardation spectrometer in the first 1.25 s and the voltage listed in the legend in the last 1.25 s. The data themselves are the integrated number of counts in the spectra.

of their axial oscillation period in the high magnetic field where their kinetic energy is fully converted to radial kinetic energy. Additionally, the cross section for ionisation will be largest for a kinetic energy $\mathcal{O}(100 \text{ eV})$. At the beginning of the measurement two sources of primary electrons are thus present; the one from a previous measurement cycle and new ones created by the γ radiation. For the subsequent measurement cycles there are only the electrons created by the γ radiation.

In figure 5.4, bottom panel, the same measurement cycle as for the top panel is shown. The difference being that instead of having ions in the decay trap, the ions were now shot onto the pumping diaphragm in the cooler trap. The goal was to see whether γ particles or β^- particles – the latter are stopped by the pumping diaphragm – cause the retardation-dependent background. Clearly the effect is attenuated; where the count rate in the last 1.25 s was clearly higher in figure 5.4, top panel, this is not so apparent anymore for this measurement. However, the peak at 1.25 s which is a tell-tale sign for ionisation processes, clearly indicates that something was still going on, even with a lower γ intensity, and a reduced solid angle. Also note the difference in count rate between the top and bottom panel in the first 1.25 s; this difference can be explained by the β 's and recoil ions being blocked by the pumping diaphragm.

After the vacuum upgrades, an on/off measurement was done with a ^{60}Co source in the decay trap. The main purpose of this measurement was to find out

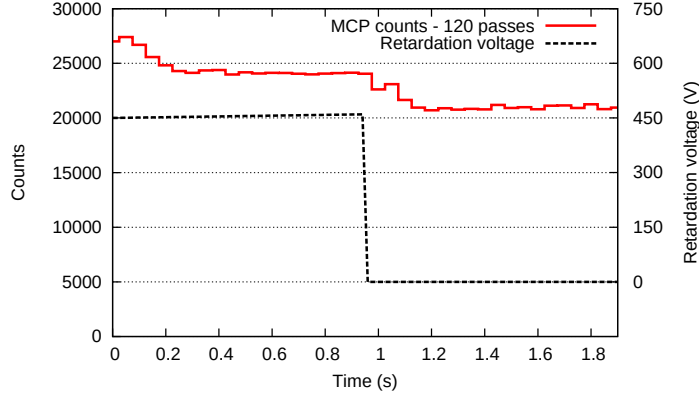


Figure 5.6 – Measurement of the ionisation created by a ^{60}Co source in the decay trap. During the first 0.95 s the spectrometer is at 450–460 V, afterwards it is switched back to 0 V.

whether there was any ionisation triggered by γ radiation left. To this end a measurement with a 1.9 s cycle was performed while the spectrometer was at 450 V in the first 0.95 s and at 0 V in the last 0.95 s. The data from this measurement is shown in figure 5.6. It has to be noted that the compensation magnet had not been installed yet at that point. Although, no discharges or peaks like in the measurements of 2006 and 2007 were observed, a small difference in count rate between the spectrometer at 0 V and 450 V was still present. A total number of ~ 900000 events are registered in the spectrum, which corresponds to about 50 counts per cycle of 1.9 s. The extra background that is created when the spectrometer is at 450 V amounts to 4 extra counts per second. Since the used ^{60}Co source (with an intensity of ~ 40 kBq) was stronger than the expected ^{35}Ar source, and because of the higher γ multiplicity of ^{60}Co compared to ^{35}Ar , the effect was deemed to be negligible during the online ^{35}Ar run. Even if the effect would still be there, it was expected that such a small effect would be drowned in the signal of the first detected recoil ions after the decay of ^{35}Ar . For a precision measurement, however, any retardation-dependent background has to be taken into account.

Unfortunately the assumption of this background being negligible for ^{35}Ar turned out to be wrong during the ^{35}Ar run of November 2009; see section 3.4.2. A retardation-dependent background was clearly present. On the one hand, the ^{35}Ar source in the decay trap during that run was obviously not sufficiently strong¹ as to produce as many γ 's per second as a 40 kBq ^{60}Co source. On the other hand, the β^+ particles from ^{35}Ar decay end up primarily inside the pumping diaphragm and the einzel lens region in the re-acceleration section, where they create 511 keV annihilation γ 's. As such, ^{35}Ar is also a γ source where for every decay 2 γ particles are created, but with a very different solid angle distribution compared to a normal γ source like ^{60}Co . This explains why

¹98.02(3) % of ^{35}Ar decays proceeds directly to the ^{35}Cl ground state, see figure E.1

the ionisation effect could be much larger for ^{35}Ar than ^{60}Co ; electrons that can be trapped in the spectrometer are probably created in the upper part of the setup (SPEINZ01 or SPDRIF01). The solid angle for γ 's from ^{60}Co is pretty low as this area is already $\sim 2\text{ m}$ away from the decay trap, while the solid angle for annihilation γ 's is larger. Note that β^- particles apparently do not cause an observable ionisation processes, as nothing was observed during measurements with an offline ^{90}Sr source. This will be explained in more detail in section 5.3.4.

Build-up Time Constant

The time scale over which ionisation processes become visible to detection is important for the implementation of solutions. If it takes for instance one minute for the ionisation effect to build up, a sweeping conductive wire [Beck et al., 2011] can be used to remove electrons from a Penning-like trap. The same is true for longer time constants. However, if the ionisation processes can produce a retardation-dependent background within one second, this already places constraints on possible solutions; i.e. a sweeping conductive wire would be too slow to suppress the occurring ionisation processes.

An example is shown in figure 5.7. The top panel shows an off/on measurement with 0 V/20 V with the switch occurring at 1.25 s. The middle panel shows the same, but with voltages of 100 V/120 V. In the first measurement (top panel) a particle trap for electrons was too shallow, and no ionisation effect can be seen. In the second measurement (middle panel) 100 V is clearly sufficient to accumulate electrons. The decreasing count rate at the beginning of the time sequence is due to a release of ions when going from 120 V to 0 V (which happens in between two measurement cycles). Each data file contains 10 spectra; as such each data file encompasses a total measurement time of 22 s. The total number of counts in one data file (for the 100 V/120 V measurement) is shown in the bottom panel of figure 5.7. As can be seen in that figure, the ionisation processes needs quite some time, i.e. $> 20\text{ s}$, to generate huge count rates. It is not sure what would have happened if that measurement had continued; the count rate might have saturated at some point or it could have become so high as to shut down the detector (see next section). Given the rapidly increasing count rate, this is probably a good example of a runaway discharge.

After the vacuum upgrades, the probability of ionisation by electron impact was already significantly reduced, but still present. An idea about the build up of electrons in a Penning-like trap in the centre of the main retardation electrode can be obtained by comparing the two panels in figure 5.8. How they were obtained is described in detail in section 3.4.2. The top panel shows a spectrum obtained by ramping the retardation voltage during each experimental cycle, while the bottom panel is constructed from several experimental cycles where the retardation voltage was kept constant during each individual cycle. The count rate for a certain voltage is very different in the two spectra. In the first spectrum the ionisation process is still in its early stage and does not generate many events that end up on the detector. In the second spectrum the ionisation process has stabilised; the total count rate for each spectrum that was used to

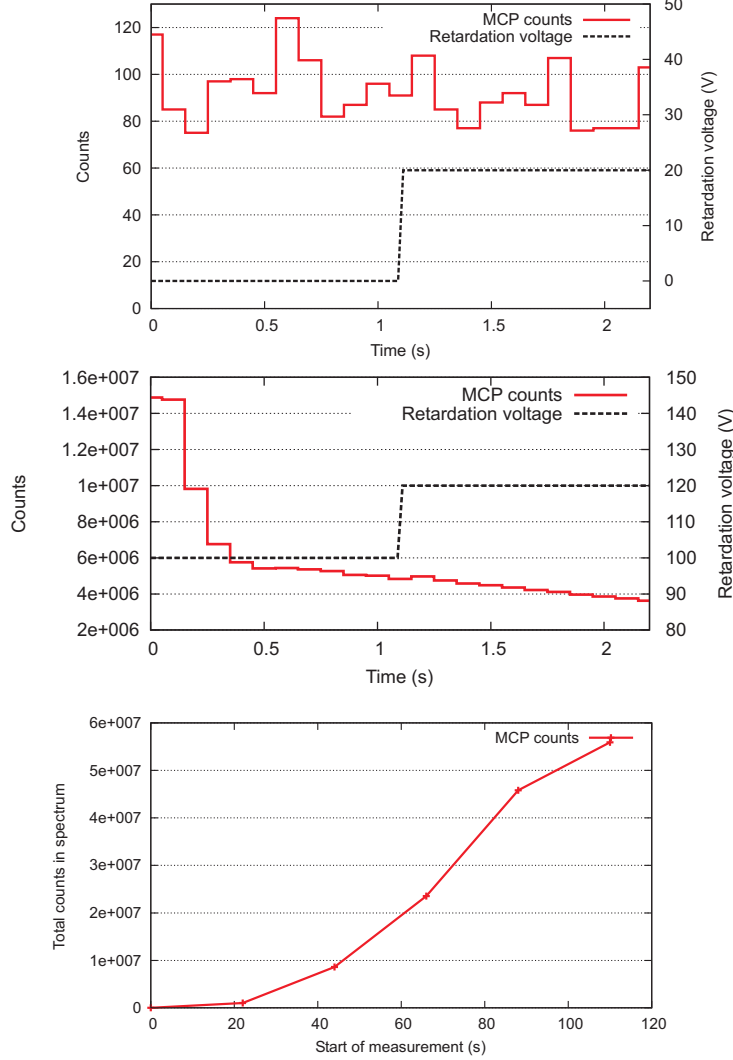


Figure 5.7 – Secondary ionisation created during an on/off measurement with ^{60}Co . In all measurements the einzel lens electrode voltage was at -140 V. In the top panel the retardation electrodes were switched between 0 V and 20 V. In the middle panel the retardation electrode were switched between 100 V and 120 V; no peak is observed when switching to a higher retardation potential. This is probably because the change of the retardation potential is rather small (i.e. 20 V). Between the end of the cycle and the beginning of a new the cycle, the spectrometer is briefly at 0 V. This spectrum consists of 120 experimental cycles, spread over 6 data files. The bottom panel shows the evolution of observed total counts in 20 consecutive measurement cycles (one data file) for the spectrum shown in the middle panel.

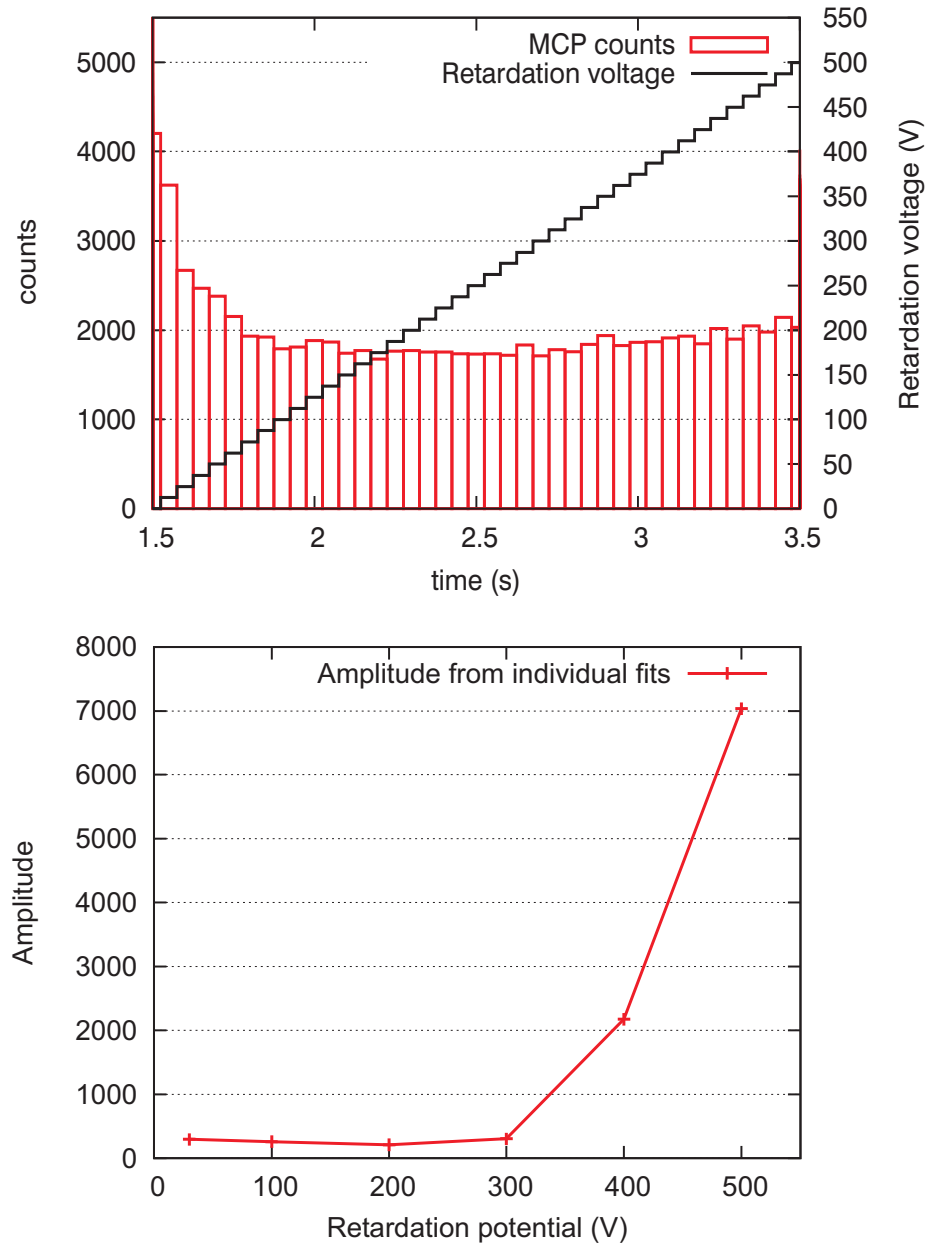


Figure 5.8 – Attempt at measuring a recoil ion energy spectrum in the decay of ^{35}Ar by ramping the spectrometer during one experimental cycle. The top panel shows a spectrum during which the voltage on the retardation spectrometer is ramped from 0 V to 500 V in 12.5 V steps. Each bin is 0.05 s long, and each bin corresponds to a different retardation voltage. The bottom panel shows a constructed retardation spectrum from several experimental cycles during which the retardation voltage was kept constant during ~ 15 minutes. The y-axis shows the amplitude of the exponential fit performed on the individual spectra.

construct the spectrum shown in figure 5.8, bottom panel, is shown in figure 5.9. From that figure it is clear that the process of ionisation has stabilised, but is still susceptible to stochastic fluctuations. When looking at one individual spectrum from figure 5.9 (see figure 3.7, top panel), however, it is clear that the discharge is not self-sustained, but correlated to the radioactive decay.

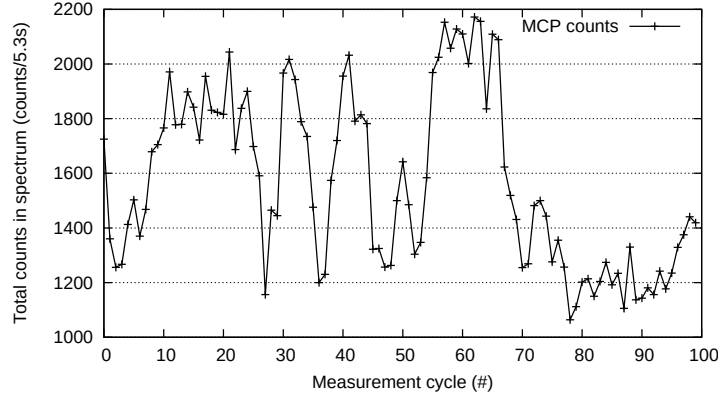


Figure 5.9 – Total count rate during each single measurement cycle for the spectrum shown in figure 5.8, bottom panel. The different count rates for separate measurement cycles is too large to be attributed to statistical fluctuations or fluctuations in the source strength. These differences are caused by the stochastic nature of the discharges.

One can draw two conclusions from these figures;

- The electron trap in the main retardation electrode needs somewhere between 0.05 s – the duration of one bin in figure 5.6 – and 5 s – the time of an experimental cycle in figure 5.9 – to stabilise,
- It is impossible to quantify these background count rates, as this fluctuates in time with the same experimental conditions due to the stochastic nature of the ionisation process.

A sweeping conductive wire is in this case not adequate. The sweeping rate of such a wire is limited by its mechanical implementation. For the wire described in Ref. [Beck et al., 2010] the maximum sweeping frequency was of the order of 1 Hz. This is too slow to stop ionisation which already disturbs the spectrum after 0.05 s (see figure 5.8). A fixed conductive wire is thus necessary to efficiently stop electrons from accumulating in the Penning-like trap in the spectrometer.

Runaway Discharges

In the previous section the time scale on which ionisation processes become visible was discussed. Depending on the conditions, the formed ionisation can

increase until the detector shuts down and electrode power supplies trip. This has been observed during measurements as well. These data show an – often exponential – increase in count rate and then suddenly nothing anymore when the detector has shut down.

Conditions which are susceptible to runaway discharges are

- Higher magnetic fields, i.e. 9 T and 0.2 T instead of 6 T and 0.1 T. The last runs were always performed with the latter configuration to lower the probability of ionisation processes.
- The absence of the compensation magnet. During the ^{35}Ar run in 2009 the ionisation was never out of control. However, at the end of the run more extreme conditions were tried, like shutting down the compensation magnet, which led to a runaway discharge within seconds. From this, one can conclude that this magnet is an important factor in the reduction of the ionisation probability.
- The vacuum in the setup. Indeed, the fact that after the upgrades runaway discharges were not seen anymore in normal conditions, shows that the vacuum plays an important role in the ionisation processes that occur in the spectrometer.

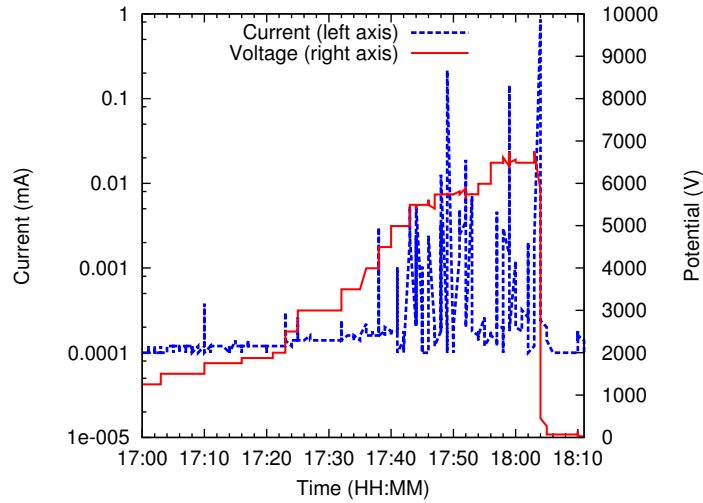


Figure 5.10 – The voltage and current delivered by the power supply of SPDRIF01 while characterising the unwanted electron trap in the einzel lens region.

An unwanted trap for electrons was the reason for the construction of the compensation magnet described in section 4.2.2. The unwanted electron trap in that region consisted of endcaps (SPACCE02 and SPDRIF01), both on a negative voltage. It was not possible to ramp up both electrodes at the same time,

because the electrons in the unwanted trap caused a discharge whenever the potential well for the electrons was too deep (and when a too high number of electrons could accumulate). The effect this has for SPDRIF01 and its power supply is shown in figure 5.10. The voltage on SPACCE02 is the same as SPDRIF01 and the voltage on the einzel lens electrode (SPEINZ01) is -500 V. From a certain voltage on, i.e. somewhere between -4 and -5 kV, the current of the power supply starts fluctuating which indicates discharges from the unwanted electron trap. When the current of the discharge is too high, the power supply shuts down as is the case at 18 : 05.

Peaks in the Spectrum

In all the spectra presented so far (figures 5.4, 5.6 and 5.7), an increase in count rate is seen when the voltage on the retardation spectrometer is switched with a large voltage difference. In figure 5.4 this expresses itself as a sharp peak in the middle of the spectrum; the peak at the beginning of the spectrum is probably overshoot of ions during the transfer of the ion cloud from the cooler trap to the decay trap. In figure 5.6 the transition from a high to a low voltage (and the reverse) is not sharply defined; the count rate slowly decreases to a stable value. In figure 5.7 there is a huge count rate at the beginning of the time sequence; the reason for this is that between two separate measurement cycles the voltage on the retardation electrode briefly goes to 0 V. Extra data supporting this discussion are retardation spectra taken during the ^{35}Ar run of 2007 (see figure 5.11).

The peaks, caused by the release or creation of particles when switching from a high voltage to a low voltage, can be explained by

- Recoil ions being trapped between the analysis plane and the high magnetic field of the Penning traps. When the voltage is switched down, they can fly through the spectrometer and be detected. However, this was simulated in the past and the recoil ions should not stay trapped for a long time; rather they return to the Penning traps and hit the pumping diaphragm or travel into the vertical beamline.
- In the same particle trap, also ions can be trapped that were created on the other side of the analysis plane (with respect to those that are detected immediately and are responsible for the retardation-dependent background).

Longer release times as shown in figure 5.11 can also be explained with Penning-like traps in the spectrometer. When the voltage on the main retardation electrode is switched off the unwanted electron trap vanishes in principle. However, a larger electron trap is also present in the spectrometer of which the endcaps are formed by the high negative potentials of the re-acceleration electrodes and the high magnetic field of the Penning traps. After the destruction of the initial trap, electrons can still linger in this second trap and cause further creation of ions. However, electrons in this trap have a lower kinetic energy and do not

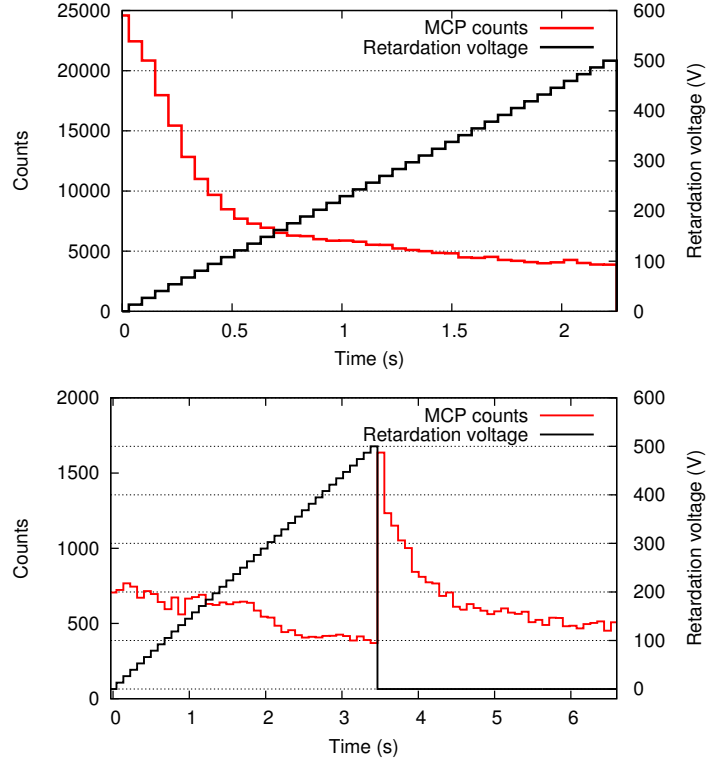


Figure 5.11 – Measurement of a retardation spectrum with a maximum retardation potential of 500 V. **Top:** The retardation potential increases to 500 V during 2.5 s, after which it is reset to 0 V until the next measurement cycle starts. This spectrum contains 1300 measurement cycles. **Bottom:** The true nature of the retardation spectrum is revealed when the measurement cycle is extended beyond the measurement of a retardation spectrum. From 3.5 s onwards the spectrometer is at 0 V. This spectrum contains 140 measurement cycles. A peak is present in both spectra, which only decreases on a time scale of the order of one second. The origin of the peak is the same; it occurs when the retardation voltage is switched from a high positive value to a low positive value.

create as much ions as electrons trapped in a high retardation potential; this is also seen in measurements where the voltage on the retardation spectrometer is low (see e.g. figure 5.7). At 0 V the background count rate from ionisation processes is lower.

The switch from a low to a high voltage (see e.g. the first 0.2 s in figure 5.6) can be explained by the fact that electrons remain trapped when the retardation spectrometer is at 0 V. During this time the electrons will have lost most of their energy and are not able to ionise helium atoms. However, when the spectrometer is switched to a higher voltage their kinetic energy will increase when they accelerate towards the analysis plane; the electrons spend most of their time in the high magnetic field. They thus have a low probability of being present in the main retardation electrode and their relative potential energy will not change by the full retardation potential during the switching. When the voltage is thus switched to a higher value there will be two sources of electrons; electrons that were trapped in the larger electron trap and new electrons created by γ radiation. The former have in addition a higher cross section for ionising a rest gas atom (see figure 5.1).

Dependence on Einzel Lens Electrode Voltage

During the ^{35}Ar run in 2009 a peculiar behaviour was observed, i.e. the count rate on the detector did not decrease with the retardation voltage. The measured spectrum shown in figure 5.8 (top panel) is only valid for a specific einzel lens electrode voltage (i.e. -600 V). When changing the einzel lens electrode voltage a bump could be seen moving through the spectrum. To investigate this behaviour further, a measurement was done with the retardation spectrometer at 500 V and by scanning the einzel lens electrode voltage; the result is shown in figure 5.12.

A pronounced peak is present at $+517\text{ V}$, a larger bump is located around 0 V and towards the more negative voltages (i.e. $< -600\text{ V}$) the count rate increases slightly. At $+700\text{ V}$ no more events are detected. This means that ions created upstream of the einzel lens electrode cannot go to the detector anymore as electrons would not be stopped by a positive potential. The potential in the centre of the einzel lens electrode is about 30 % lower than the voltage applied on its surface. Especially the fact that the maximum in the count rate occurs when the spectrometer and the einzel lens electrode are at almost the same voltage is of interest; with the spectrometer at 500 V a maximum is observed when the einzel lens is at 517 V. Two tentative explanations can be given;

- Since 517 V on the einzel lens electrode does not correspond to a potential of 517 V in the centre of the electrode, some ionisation process might be at work on the surface of the einzel lens electrode. Indeed, after the installation of the compensation magnet, the surface of this electrode and the centre of the main retardation electrode are connected to each other via magnetic field lines (see figure 4.6).
- The ions are created in the spectrometer. The count rate at different einzel lens electrode voltages is a focussing effect.

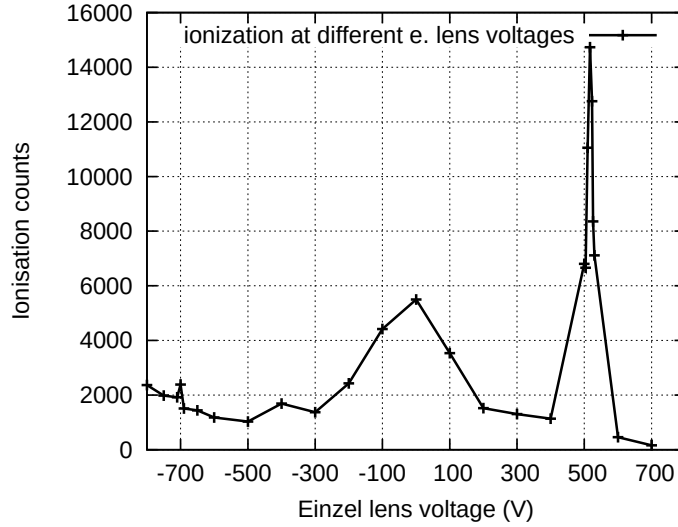


Figure 5.12 – Graph showing how the number of detected counts varied depending on the einzel lens electrode voltage, with the retardation spectrometer fixed at 500 V. The settings for the re-acceleration electrode and detector were the following; -2 kV for SPACCE01, -8 kV for SPACCE02, SPDRIF01 and SPDRIF02, and -6 kV for the front plate of the detector. For each data point the count rates of ten experimental cycles – with a duration of 5.25 s – were integrated.

The simulations that will be presented in section 5.3, can reproduce the peculiar shape of this measured spectrum. The conclusion is that the ions are created in the spectrometer and the increase in count rate can be explained by different focussing of the ions onto the detector. It has to be noted though, that this behaviour was only present when positive voltages were applied to the retardation spectrometer electrodes.

5.2.4 Other Locations of Penning-like Traps

For completeness, other unwanted particle traps that have been observed in the system are also discussed here.

In the VBL

In section 5.1.3 the possibility of an unwanted trap in the vertical beamline was already mentioned. It seems that this trap can create ions under certain conditions, but this is very dependent on the beam tune. This trap will not disturb the measurement of a recoil ion energy spectrum, but it can be misleading during the setup period for an experiment. During the beam tuning it should be checked at all times whether the detected signal originates from the expected

ions or from ionisation. This can be done by deflecting the ion bunches on purpose (i.e. by setting the beamgate to a wrong timing value, or by changing the voltage of a steerer, kicker or bender electrode).

In the traps

Ionisation is observed in the cooler trap when vacuum conditions are not great – i.e. shortly after pump-down –, if the endcap electrode voltages are switched to a voltage exceeding 70–100 V and with normal buffer gas pressures. This effect could be caused in conjunction with the unwanted Penning-like trap in the VBL. With the endcap electrodes at a high (positive) voltage, a trap is formed for electrons in the endcap region. Some measurements done with a ^{60}Co source in the decay trap are shown in figure 5.13. Measurements are shown where the spectrometer is switched between 0 V and 400 V, and the upper endcap electrode of the decay (DEE6) is switched between 0 V and 200 V. This particular combination of fields will not occur during an experiment; the voltage on the endcaps of the decay trap is too high. However, it gives a clue as to how the ionisation in the cooler trap is created.

The observed behaviour shown in figure 5.13 can be explained if one makes two assumptions

- A Penning-like trap for electrons is formed when DEE6 is at a high positive potential. The trapped electrons will ionise rest gas atoms that can be accelerated towards the detector.
- A Penning-like trap for electrons exists in the spectrometer when it is at a high positive potential, again creating ions.

Looking at the top panel the count rate can be explained as follows. When the voltage on the endcap electrode is increased, ions are created because of the electron trap and are accelerated towards the detector. When the voltage on the retardation spectrometer increases, the count rate drops as the ions that are created in the endcap region cannot pass the retardation barrier anymore. However, a slightly higher count rate than the background (e.g. between 0–0.4 s) is still observed; this is similar to what is seen in figure 5.6 in the first 0.2 s. It is an increased count rate due to a voltage switch on the retardation spectrometer from 0 V to 400 V. When the voltage on the endcap electrode is lowered, some of the electrons that were trapped in the endcap electrode will go to the spectrometer and remain trapped there. These electrons trapped in the spectrometer will ionise rest gas atoms, creating a drastic increase in the count rate. The count rate is decreasing because these electrons will lose energy due to ionisation of rest gas atoms and after a while they will not have sufficient energy for this anymore. The difference in count rate between the period of [0.5 : 0.6] s and [1.2 : 1.5] s is similar to figure 5.6; the period of [0.5 : 0.6] s corresponds to the first 0.2 s in that figure, while the period of [1.2 : 1.5] s rather corresponds to a time range where the count rate is constant. The small increase of the count rate in [1.2 : 1.5] s is caused by the switching of the endcap electrode voltage;

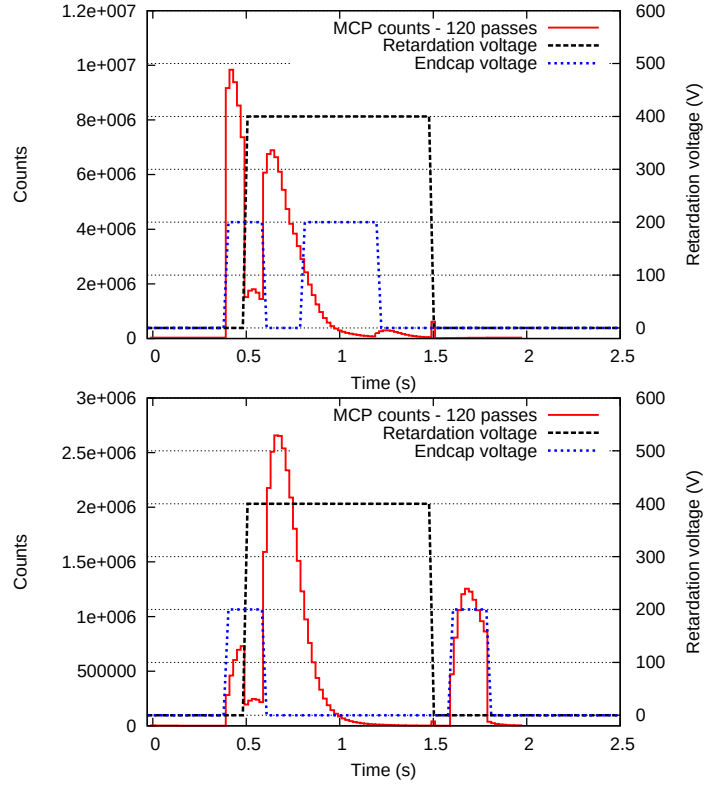


Figure 5.13 – Spectrum measured during a switch of the spectrometer and the upper decay trap endcap. At 0.5 s the spectrometer is raised to 400 V, at 1.5 s it is lowered to 0 V. In the left figure the endcap is raised during [0.4 : 0.6] s and [0.8 : 1.2] s. In the right figure it is raised during [0.4 : 0.6] s and [1.6 : 1.8] s.

in this process the trapped electrons can gain some kinetic energy which allows them to ionise atoms again for a short period. Similarly the bottom panel can be explained as well; the ions created by the second increase of the endcap electrode voltage is only possible because the spectrometer voltage was switched down for 0.1 s already. Otherwise the experimental cycle in the two panels is the same, but note that the observed count rate can greatly vary; i.e; between 0.4 s and 0.5 s.

Concluding, a Penning-like trap for electrons is indeed present in the endcap region of the decay trap, so this is also true for the cooler trap. If these unwanted traps can be loaded with electrons they will indeed ionise buffer gas and rest gas, that can be trapped in the cooler trap. In itself this does not disturb a measurement, but it renders the preparation of the wanted ion species more difficult and a proper optimisation is very difficult under these circumstances.

5.2.5 Summary of Observations

Summarising all the measurements of the ionisation that hamper a measurement of a recoil ion energy spectrum, one can distinguish the following effects and unwanted traps;

- The background depends on the retardation voltage and the γ (or β^+) intensity. Without γ radiation this effect is not seen. β^- radiation alone is not sufficient to trigger the effect in the performed measurements. With β^+ radiation annihilation γ 's are created in a part of the system that is much more susceptible to the creation of electrons (compared to γ 's originating from the decay trap). This can be explained with an electron trap present in the centre of the main retardation electrode.
- Switching the spectrometer electrodes creates peaks or a slow release of ions. These are ions that are trapped between the analysis plane and the high magnetic field of the Penning traps. Additionally, increasing the voltage on the spectrometer also briefly increases the observed count rate. Both effects can be explained in terms of two electron traps and one ion trap in the main retardation electrode.
- The upgrades were successful in reducing the probability of ionising processes P_{ion} occurring; e.g. runaway discharges have not been observed afterwards. Random fluctuations in the spectra are also not observed anymore. The installation of a compensation magnet removed the unwanted trap in the einzel lens region.

Based on the observations an *ad hoc* solution was installed in the spectrometer; a conductive wire through the analysis plane in the retardation spectrometer and perpendicular to the magnetic field axis (see section 5.4). The peculiar spectrum shown in figure 5.12 will be used to gain more knowledge about the ionisation processes at play with the aid of simulations (see next section).

5.3 Simulations

As was discussed, the behaviour of the ionisation effect in the spectrometer that has been observed over the years can be explained by the presence of two Penning-like traps for electrons, one in the centre of the main retardation electrode and another one in the centre of the einzel lens electrode (see Fig. 5.3). The latter has been eliminated by altering the magnetic field in the einzel lens region with the installation of a new magnet (see section 4.2.2). A possible solution for the electron trap in the centre of the main retardation electrode has been implemented recently as well, and has undergone testing already (see section 5.4). The aim of the simulations discussed in this section is to strengthen the hypothesis of a Penning-like electron trap in the centre of the main retardation electrode and to learn more about the ongoing ionisation processes. To this end reproducing the spectrum that shows a dependence on the einzel lens

electrode voltage (figure 5.12) is the main goal. In the following, figure 5.12 will be referred to as the ‘*einzel* lens electrode spectrum’.

5.3.1 Approach

A pragmatic approach has been taken for the localisation of possible ionisation events in the system. Ions were created all over the system – with different electric field configurations – and tracking simulations were performed to see where the created ions end up on the detector. The ionisation processes themselves were thus not simulated. By combining the data from these simulations one can select volumes in the spectrometer where the created ions reproduce the observed dependence on the *einzel* lens electrode potential.

The simulations were done with the simulation package SimWITCH [Friedag, 2008, Mader, 2010, Friedag, 2012]. In principle it is a Monte Carlo simulation package, but an extra module has been added to create ions with well-defined properties and positions – on a grid –, instead of in a random manner. This simplifies the comparison of ion tracks in different electric fields. In the end the following starting conditions were chosen;

- The energy of the ions was chosen to be rather low. When an electron ionises an atom there will be a negligible velocity change for the newly created ion. One can thus assume that the created ions obey a Maxwell–Boltzmann velocity distribution at room temperature. Since the initial energy of the ions has a low impact on its eventual track, an energy of 0.5 eV was chosen. With the same argument, the initial angle is not really important, even though several angles were selected.
- The mass of the ionised atoms is in principle unknown. This depends on the ionisation mechanism. If ions are created from rest gas atoms, its mass can correspond to that of oxygen, nitrogen, water or helium. Masses of $4u$ and $28u$ were chosen as the latter lies close to masses of previously observed ionisation in the traps, e.g. N_2^+ and CO^+ , while the former is the mass of helium buffer gas atoms.
- The starting positions of the ions were chosen close to the surface of the *einzel* lens electrode and in the centre of the main retardation electrode.
- The voltage of the retardation spectrometer was taken to be +500 V, while the *einzel* lens electrode voltage was variable. Each *einzel* lens electrode voltage requires another simulation.
- The inhomogeneity of the detection efficiency over the detector surface was taken into account, based on measurements with a ^{241}Am source (see section 6.3.3). These measurements showed that the efficiency in the centre of the detector is heavily decreased, while in the outer rim the efficiency has degraded much less.

Note that the starting positions of the ions correspond to a two-dimensional grid, but because of the cylindrical symmetry of the system this effectively probes a

three dimensional volume with proper scaling; the number of ions created at a certain radius was multiplied, in the analysis, with a factor of $2\pi r$ to take into account the fact that more ions are created at a larger radius for an unwanted trap where the electrons are homogeneously distributed.

5.3.2 Location of the Electron Trap

In initial simulations it was checked whether the observed ions originate from the centre of the main retardation electrode or from the einzel lens electrode surface. Examples of simulated tracks for both cases are shown in figure 5.14. Ions created on the einzel lens surface exhibited very chaotic behaviour; their final position on the detector is very sensitive to the initial starting conditions. Most created ions, however, do not end up on the detector. Therefore, ions created on the surface of the einzel lens electrode were not considered anymore as the source of the ions that were detected in the einzel lens electrode spectrum.

The ions created in the spectrometer exhibited more predictable behaviour; at different einzel lens electrode voltages the focus onto the detector is slightly different. In itself this is not enough to reproduce the einzel lens electrode spectrum. However, if the inhomogeneous detection efficiency is taken into account, a slightly different focussing can cause a large deviation in the observed count rate on the detector.

5.3.3 Fitting the Einzel Lens Electrode Spectrum

For the final simulations ions with mass $28u$ (i.e. N_2 and CO) and mass $4u$ (i.e. He) were created on a grid with a spacing of two millimetres. They were created in a volume up to a radius of 15 cm and from axial positions of $z = 0.9\text{ m}$ – the analysis plane – to $z = 1.3\text{ m}$ – the start of the re-acceleration section. To simulate an electron trap with a homogeneous spatial distribution, the count rate of detected ions was weighted based on their initial starting radius.

In the analysis it was checked whether ions from a certain start volume could reproduce the einzel lens electrode spectrum. Different volumes that are ‘physically possible’ were considered in this; volumes always include the centre of the main retardation electrode (radially and axially). If only ions created at $r = 0.1\text{ m}$ and $z = 1.0\text{ m}$ reproduce the einzel lens electrode spectrum, this would be hard to motivate from a physical point of view. Electrons that ionise an atom at $z = 1.0\text{ m}$, for instance, will move through the centre of the trap at $z \approx 0.9\text{ m}$ as well and have a probability to also ionise atoms there. The best match between simulations and the experiment is shown in figure 5.15; in the case of helium atoms this is realised for an electron trap with a radius of 1.8 cm of which the length is not so important. The optimal radius can change by 1–2 mm depending on what radial distribution is used for the electron trap; 1.8 cm is the optimal radius for a homogeneous distribution, while 2.0 cm is the optimal radius for a Gaussian distribution.

Some mismatch between the simulations and measurements is present. The

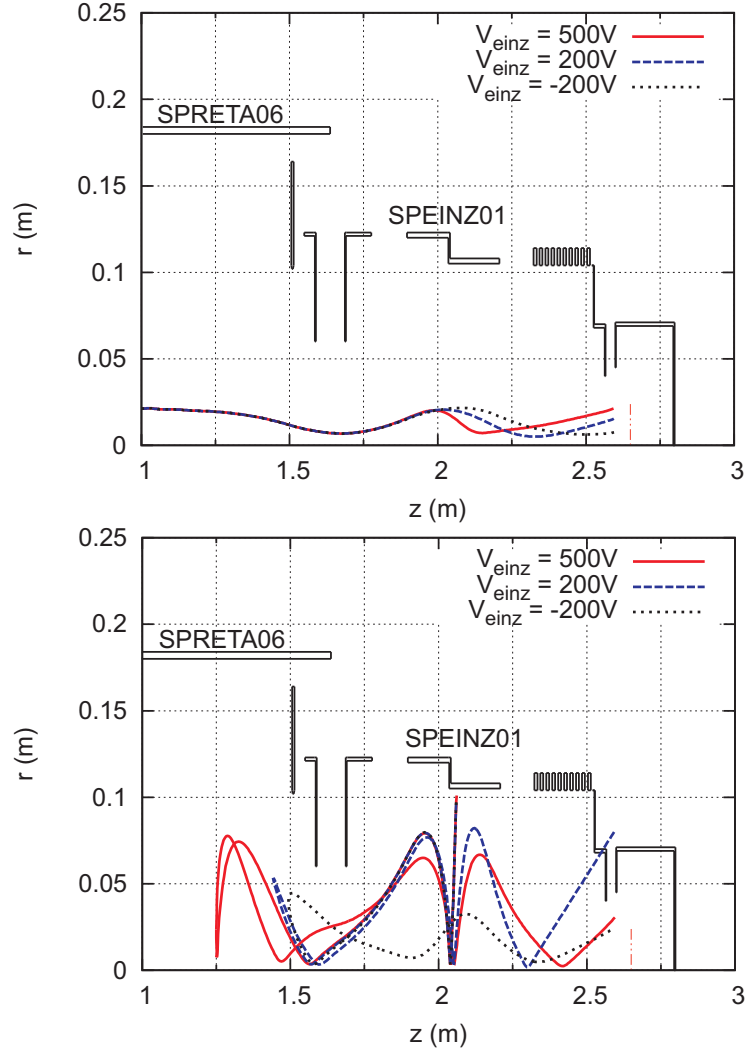


Figure 5.14 – Example of simulated ion tracks in the system. In both figures the main retardation electrode (SPRETA06) is at 500 V, while the einzel lens electrode (SPEINZ01) is kept at three different voltages. The other electrodes have the same voltages as in figure 5.12. In the **top** panel the ions are created close to the analysis plane in the spectrometer; this figure is representative for many created ions in the spectrometer. The created ions are focussed towards the detector and end up on different areas of the detector because of the different focussing due to different einzel lens electrode voltages. In the **bottom** panel the ions are created close to the surface of the einzel lens electrode (SPEINZ01); this figure is not representative for most of the created ions. The ions are then first guided towards the traps and reflected on the analysis plane. After reflection they are focussed towards the detector and end up at very different positions of the detection plane.

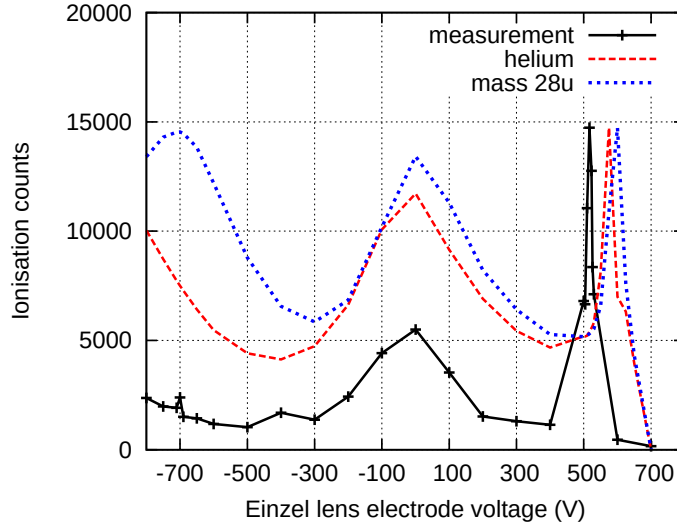


Figure 5.15 – First the same spectrum as in figure 5.12 is shown (full black line). The other lines are from simulations for mass 4 (red dashed line) and mass 28 (blue dotted line) for starting positions of the ions showing the best correspondence with the measured spectrum.

einzel lens voltage at which the ionisation peak occurs is slightly shifted. However, additional simulations have shown that different voltages on the re-acceleration electrodes or the detector can easily shift the position of this peak. Also the axial position of the detector is important for ions being focussed onto it [Mader, 2010]. Based on simulated particle tracks one can explain the measured einzel lens electrode spectrum in terms of beam optics. At a certain einzel lens electrode voltage (i.e. -600 V for recoil ions from ^{35}Ar decay if the surrounding electrodes are at -8 kV) the focussing of ions onto the detector is optimal. In this case, with a detector that is degraded in the centre, the count rate is minimal. For a lower einzel lens voltage, the convergence of particles onto the detector will be lower; they will then end up on the outer rim of the detector and show up in the measurement. If the convergence (focussing) is too strong – for higher einzel lens electrode voltage (e.g. 0 V) – the focal point will lie in front of the detection surface and the ions will be focussed on the outer rim of the detector again. This explains the peaks at 0 V and the increasing count rate towards very low voltage (i.e. -800 V). The peak around ~ 517 V (in the measurement) is hard to explain in terms of light optics.

Rather, one has to look at the electric field gradient in the einzel lens electrode for this (see figure 5.16). First of all the magnetic Lorentz force is negligible in the einzel lens electrode; this was checked with different magnetic field configurations showing no influence on the tracks of the particles in this region. Then the electric field gradient in the einzel lens electrode is important. The potential applied to the surface of the einzel lens electrode, i.e. 575 V in the simulations,

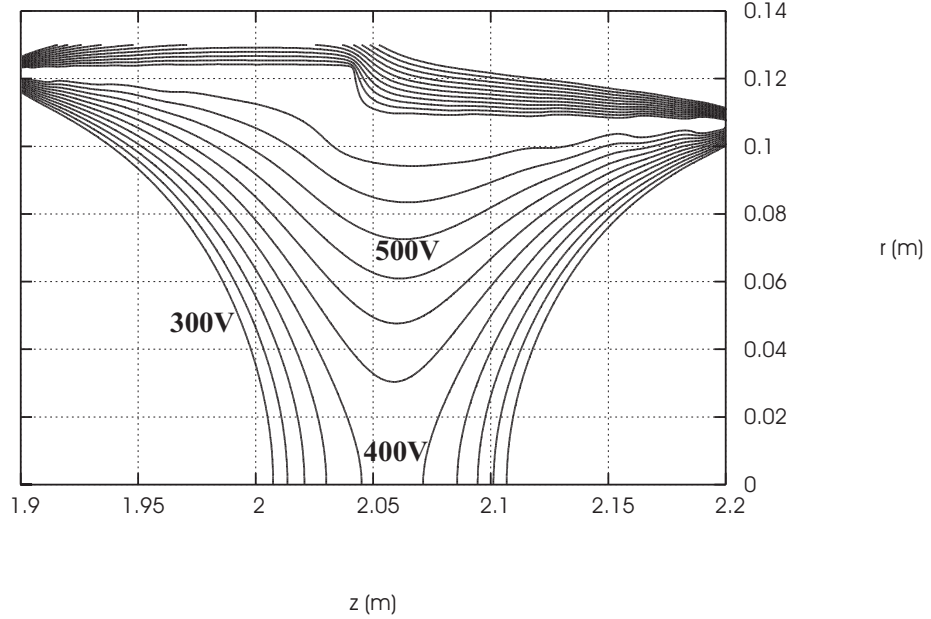


Figure 5.16 – Contour plot of the electric potentials in the einzel lens electrode region with the einzel lens electrode at 575 V and the surrounding electrodes (SPACCE02 and SPDRIF01) at -8 kV. The outer contour is an equipotential line for 300 V. Every contour closer to the surface of the einzel lens electrode shows an increase in the potential of 25 V. The innermost contour – basically close to the einzel lens electrode surface – is for a potential of 550 V.

is too high for ions created at a potential of 500 V to pass. However, in the centre of the electrode the potential is only ~ 407 V for the configuration used in the simulations, which is sufficiently low for the ions to pass. Ions arriving in the einzel lens region at a radius of the order of a few centimetres will be guided by the electric field gradient towards the centre of the electrode. The subsequent re-acceleration by SPDRIF01 will give rise to the very different focussing behaviour of the ions in different electric potentials of the einzel lens electrode, as observed in figure 5.15.

5.3.4 Discussion

With the unwanted electron trap located within a cylindrical volume with a radius of 1.8 cm (where the axial length is not so important) in the centre of the main retardation electrode, the ionisation mechanisms for such a trap can be investigated further; the process of creating a primary electron up to an ion contributing to the background count rate will be explained in detail. Also, the consequences for future measurements are looked at in more detail.

Location of Primary Ionisation Events

In figure 5.17 three things are shown. The volume within which helium ions – with an initial kinetic energy of ~ 0.5 eV – get focussed onto the detector is shown in dotted black lines. The same thing for mass $28u$ is shown in dashed red lines. For helium the volume has a radius of ~ 3 cm extending from the analysis plane to the centre of SPRETA07. For mass $28u$ ions, the radius is about 5 cm. However, only the helium ions that are created within a radius of ~ 1.8 cm reproduce the einzel lens electrode spectrum. This means that there are not enough electrons outside this volume to cause noticeable ionisation processes; otherwise these would be detected as well.

The electrons that are present in the electron trap need to originate from somewhere else. The location of the primary ionisation events can be seen by looking at a flux tube in the spectrometer with a radius of 1.8 cm. A flux tube is a volume – in this case around the central axis – where the magnetic flux, $B \cdot A$, stays constant. If the magnetic field is decreased, the surface has to increase. In figure 5.17 this flux tube is indicated by the gray area. Towards the lower magnet, which can produce a field up to 9 T, the radius of the flux tube is about 2 mm; this is small enough to go through the pumping diaphragm in the traps and into the vertical beamline. Towards the detector the radius of the flux tube gets much larger and at the location of the einzel lens electrode the flux tube crosses the electrode surface (the installation of the compensation magnet does not change this appreciably). This means that the initial electrons for the unwanted electron trap in the centre of the main retardation electrodes have been created on SPEINZ01, SPDRIF01, SPDRIF02 or the detector. This result is in agreement with measurements; the ionisation effect is much more pronounced for β^+ particles than for γ radiation. Already in section 5.2 the hypothesis that the primary ionisation events would happen somewhere in the einzel lens region was put forward. This was based on solid angle arguments. The simulations now confirm this.

Electrons can be created by γ radiation via the photoelectric effect, Compton scattering or pair creation. For 511 keV annihilation γ 's from ^{35}Ar decay, Compton scattering will be the dominant effect and pair creation is energetically not possible. For γ 's with an energy of 500 keV the cross section for photoelectric emission of an electron is $1.41 \cdot 10^{-29} \text{ m}^2$ and for Compton scattering it is $\sim 7.5 \cdot 10^{-28} \text{ m}^2$ [Grodstein, 1957]. In the former process they will have a kinetic energy close to energy of the γ radiation, while in the latter case they can exhibit all possible kinetic energies from 0 eV to 511 keV. For the creation of an electron from an iron electrode by a 511 keV photon, the probability is of the order of 6 %. Of course, a photon releasing an electron from the electrode via Compton scattering is still able to repeat this process. And for each decaying ^{35}Ar nucleus, two annihilation γ 's are created. β^+ particles impinging on an electrode can backscatter or cause electrons to be emitted from the surface as well. In iron this secondary yield is highest for electrons impinging with an energy of 300 V; it is unity for that energy [Kanaya & Kawakatsu, 1972]. For ten times higher energies (3 keV) this yield is already reduced by a factor of two. This continues to decrease for higher energies; this can also explain why

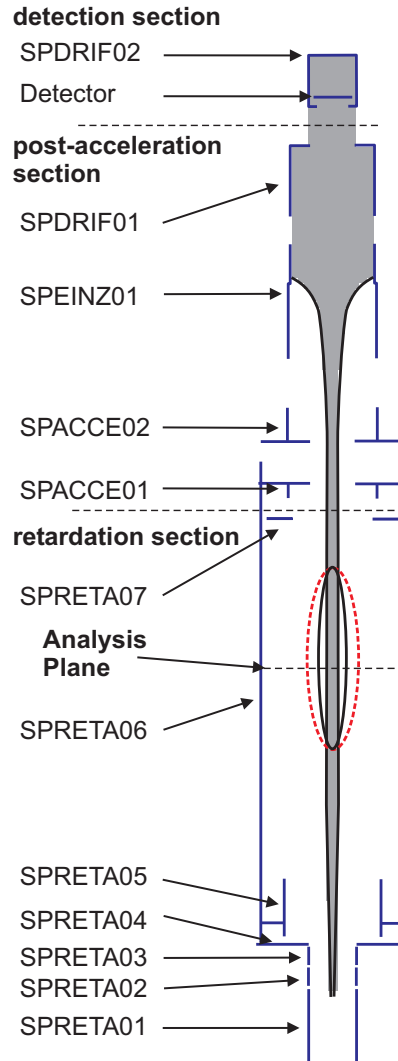


Figure 5.17 – Drawing of the retardation spectrometer. On it three different things are indicated. The volume that is enclosed in a red dashed line contains ions with mass $28u$ that get focussed onto the detector. The black dotted line indicates the same for helium ions. Ions that are created outside these volumes in the spectrometer will not be focussed onto the detector. Also indicated is the flux tube of an unwanted electron trap with a radius of 1.8 cm in the main retardation electrode. This flux tube gets much more narrow ($\sim 2\text{ mm}$) in the high field region. In the einzel lens electrode it crosses the electrode surface. This flux tube basically indicates the area in which electrons can travel; they cannot cross the boundary of the flux tube.

no ionisation effect was observed for the ^{90}Sr source which had a rather low activity.

However, whether these electrons stay trapped in the main retardation electrode still needs to be worked out. Electrons created from those electrode surfaces will first of all have to get into the volume of the main retardation electrode. To this end they need to pass the potential barrier created by SPACCE01 and SPACCE02 which is about -8 kV and they also have to overcome the magnetic mirror, since the magnetic field around the detector has a value of around 0.001 T due to the compensation magnet. The criterion for reflection from a high magnetic field is:

$$\frac{v_{\parallel}}{v_{\perp}} \geq \sqrt{\frac{B_{\max}}{B_{\min}}} - 1 \quad , \quad (5.5)$$

with $v_{\parallel}$ ($v_{\perp}$) the velocity component of the electron upon creation parallel (perpendicular) to the magnetic field line, $B_{\max}$ the maximum magnetic field of the mirror and $B_{\min}$ the magnetic field where the electron is created. The electrons will thus require a minimal kinetic energy of $\sim 8\text{ keV}$ along the magnetic field lines to arrive in the main retardation electrode, but it is very likely that the total kinetic energy is much higher due to the conversion of axial energy to radial energy when going from the low magnetic field (0.001 T) in the einzel lens region to the high magnetic field (0.1 T) in the retardation spectrometer.

The fact that the electrons need to have a high kinetic energy is easily satisfied; the primary electrons are emitted from the electrode surfaces – which can be at a high negative potential, like SPDRIF01 – by γ radiation with an energy of 511 keV in the case of ^{35}Ar . When the ions do not make it into the main retardation electrode – because their kinetic energy along the magnetic field lines was not sufficiently high – they return to their point of origin where they can release a new electron that will be emitted at a different angle. This process can repeat itself many times until the electrons manage to travel into the main retardation spectrometer or until they have lost so much energy compared to the initial primary ionisation event that their kinetic energy is lower than 8 keV .

When an electron passes the potential barrier formed by SPACCE01 and SPACCE02 it will fly through the main retardation electrode and end up in the high magnetic field region (9 T) close to the Penning traps. There it encounters another magnetic mirror; it is very likely that they will be reflected off this one, or otherwise they just fly into the vertical beamline. The maximum angle the electrons can have with respect to the magnetic field line at their creation point is 0.74° in order not to be reflected, assuming that the magnetic field is 0.001 T where they are created. Part of the radial kinetic energy radiates away due to synchrotron radiation in the high magnetic field [Jackson, 1999];

$$\frac{1}{\tau} = \frac{\dot{E}_{\perp}}{E_{\perp}} = 0.4 \left(\frac{B}{1\text{ T}} \right)^2 \text{ s}^{-1} \quad , \quad (5.6)$$

which has a time constant τ of 70 ms in a 6 T magnetic field. This is, however, too long to explain why an electron would radiate away enough energy to stay trapped; it is very unlikely that a primary electron will stay trapped via this

energy loss mechanism. Using equation 5.2 the probability of a primary electron creating a secondary electron can be calculated. For a path length of the order of a few metres, a helium rest gas with a pressure of $5 \cdot 10^{-7}$ mbar (close to the trap region) and a temperature of 293 K, this probability is about $5 \cdot 10^{-6}$. Many primary electrons (of the order of 10^6 electrons) are thus necessary to create a few electrons in the spectrometer, which will then remain trapped. Electrons that do not create a secondary electron will go back to their region of origin and can create new electrons there. So eventually some primary electrons might create secondary electrons in the spectrometer. This is similar to the creation of an electron from an electrode surface by a β particle coming directly from the decay (see above). The initial kinetic energy of the secondary electrons in the spectrometer is low; the cross section for primary electrons of 2 keV to create an electron at low energies (4 eV) is almost two orders of magnitude higher than the creation of secondary electrons with a somewhat higher energy (~ 150 eV) [Peterson et al., 1972]. Thus, even if the primary electrons that are considered here can have a relatively high energy ($\mathcal{O}(100 \text{ keV})$), most secondary electrons will have an energy low enough to stay trapped in the centre of the main retardation electrode.

Secondary electrons have a high probability of being created in the high magnetic field region where only part of the full retardation potential is applied, compared to being created in the volume of the main retardation electrode, as they spend more time there. Thus, a large contribution to their kinetic energy in the spectrometer, will come from the subsequent acceleration towards the analysis plane. If the retardation potential is a few 100 V, this will give the secondary electrons a maximum kinetic energy of the order of $\mathcal{O}(100 \text{ eV})$; in this energy range the cross section for ionisation is highest (see figure 5.1). The secondary electrons will thus easily create tertiary electrons which will continue this process. The tertiary electrons, which are trapped by the positive potential of the main retardation electrode, will have the highest probability of creating ion–electron pairs in the two ‘endcap’ regions of the electron trap, allowing the process to continue. Finally, the ions from ion–electron pairs created upstream of the analysis plane, will be focussed onto the detector and contribute to the background count rate as was observed in the measurements described in section 5.2.

To summarise; electrons are created by β radiation or γ radiation in the upper part of the spectrometer. Some of the electrons will penetrate into the spectrometer volume, where they will be reflected by the high magnetic field of the Penning traps. The probability of a primary electron creating a secondary electron, that will remain trapped, is very low. However, the primary electrons can return close to their point of origin and create new electrons that can again travel into the spectrometer. The secondary electrons that stay trapped in the spectrometer have a high probability of being created in the high magnetic field close to the Penning traps. This model gives additional insight into some observed phenomena from section 5.2.3;

- The retardation-dependent background (see e.g. Fig. 5.4) is not necessarily caused by more electrons being trapped for a retardation potential of

+500 V with respect to 0 V. However, the initial secondary electrons have more kinetic energy in the spectrometer and can thus create more tertiary electrons. It is not excluded that the secondary electrons created with a retardation potential of 0 V do not create any tertiary electrons (and thus an increased background signal on the detector), however, this rate will be lower.

- The increased count rate, and also the time constant of this, when switching from a low to a high retardation potential (see e.g. Fig. 5.6) can be explained in more detail as well. The axial oscillation of electrons with a maximum kinetic energy of 500 eV will have a frequency of ~ 4 MHz if they are trapped in the spectrometer. The path length of an electron during one period is ~ 2 m. This leads to an ionisation probability of $\sim 1.5 \cdot 10^{-5}$ per oscillation period for $\sigma_{\text{ion}} = 2.5 \cdot 10^{-21} \text{ m}^2$ and in the helium rest gas conditions used before. An electron trapped in the spectrometer with a kinetic energy of 500 eV can thus ionise about 60 rest gas atoms in one second, energy losses not taken into account. A kinetic energy of 500 eV is sufficient to ionise about 20 helium atoms (of which the electrons have a binding energy of 24.6 eV for the first ionisation); after 1/3 of a second the electron will have lost all its kinetic energy. This time of about ~ 0.3 s is in good agreement with the measurements; the time-width of the peaks/bumps when switching from a low to high voltage in the retardation spectrometer is similar (0.1–0.2 s).

With the help of measurements and simulations all ongoing processes can be understood down to the microscopic level.

Influence of the Ionisation Effect on the Recoil Ion Energy Spectrum

With a plausible origin for the secondary ionisation given, one can now predict how the ionisation effect would express itself in the future, if it shows up again. Even with a detector with a homogeneous detection efficiency the background caused by the ionisation might not be perfectly flat. Figure 5.18 shows the effects of the ionisation with a fixed spectrometer voltage (500 V) as a function of the einzel lens voltage. I.e. this is what we should have observed instead of figure 5.12 during the ^{35}Ar run in 2009 if the detector would have been working perfectly. For increasing einzel lens electrode voltages (i.e. > 100 V) the count rate is decreasing; ions are defocussed by the einzel lens and start to miss the detector. The peak around 575 V can be explained in the same way as before; ions are almost fully stopped which causes the electric Lorentz force to be more important than the magnetic Lorentz force and this causes the ions to be accelerated along the electric field gradient in that region. This type of measurement is a good method – next to an on/off measurement to see a retardation-dependent effect – to check if there are any ionisation processes at play in the spectrometer.

The reverse measurement – keeping the einzel lens electrode voltage fixed and changing the voltage on the spectrometer, as is the case during the measurement

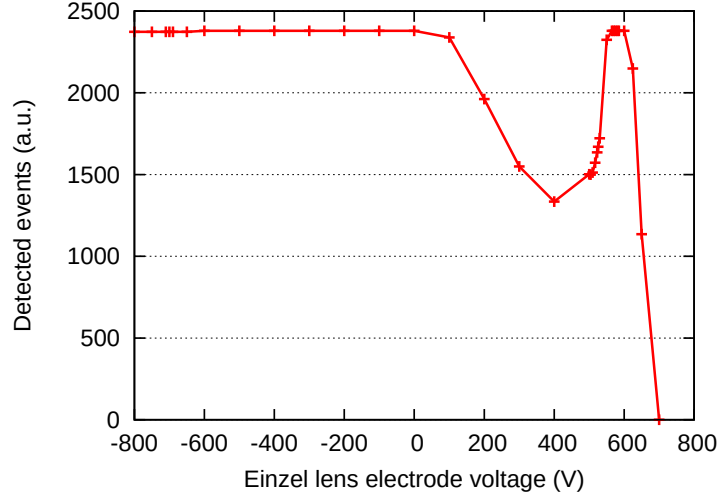


Figure 5.18 – The signature of ionised helium created in a volume within the main retardation electrode with a radius of 1.8 cm and from $z = 0.9$ m to $z = 1.15$ m, under the assumption of a homogeneous detection efficiency over the detector surface. This figure has to be compared with figure 5.12 where the detection efficiency over the detector surface was not homogeneous.

of a recoil ion energy spectrum – shows how the ionisation will influence a recoil ion energy spectrum (see figure 5.19). This figure does not show the full picture, however, as the amount of electrons in the unwanted electron trap – and thus the count rate of ions from ionisation events – will depend on the retardation potential. The more positive the retardation potential, the larger the ionisation effect. So instead of figure 5.19 the ionisation effect will rather increase at higher retardation voltages like in figure 5.8.

One can easily characterise the ionisation effect with an offline source. However, during a radioactive run this is slightly more complicated as there are also recoil ions present in the system. This can be prevented by setting the upper endcap to a high potential. Unfortunately this does not allow a quantitative characterisation of the ionisation effect as it is not constant in time (see figure 5.9). Prior to an experimental run one has to make sure that the ionisation effect is sufficiently suppressed; possible solutions are discussed in the next section.

5.4 Solutions and Design Considerations

The inclusion of the compensation magnet, the better vacuum and the electropolishing of the re-acceleration electrodes reduced the ionisation effect significantly, but not completely. So additional solutions had to be implemented

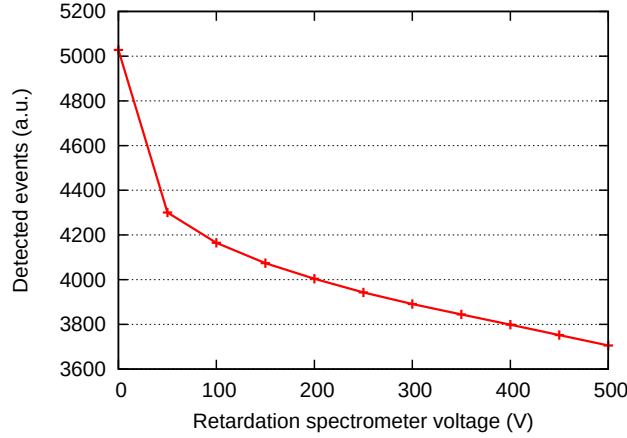


Figure 5.19 – *The signature of ionised helium created in a volume within the main retardation electrode with a radius of 1.8 cm and from $z = 0.9$ m to $z = 1.15$ m, with the einzel lens electrode voltage fixed at -600 V and the voltage on the main retardation electrode changing.*

to remove the electron trap in the spectrometer. It is not possible to change the magnetic field configuration in that region as the magnetic field there is a crucial element of the retardation spectrometer. Another solution is to remove the electrons in the Penning-like trap by other means.

Solutions to remove or reduce the secondary electron yield are;

- The installation of grids at a slightly more negative potential on top of the electrodes in the re-acceleration section. The ‘shielded’ electrodes can still create electrons, but they will be reflected immediately by the grid, thus removing the loading mechanism for the electron trap in the spectrometer. The difficulty lies in identifying the electrodes which load the unwanted trap. Also the energy of the created electrons has to be sufficiently low to be stopped by the grid.
- Thorough surface treatment by heating or charged particle bombardment to avoid the formation of an oxide layer or adsorbed gas will reduce the probability of electrons being created on the electrode surfaces. Additionally, the electrodes can be coated with a layer that reduces electron emission. Elements with a low Z should be suited for this, but also NEG coatings have been reported to reduce the secondary electron yield [Henrist et al., 2001]. However, there is no guarantee that the unwanted trap will not be loaded any longer.
- Another option would be to induce a large asymmetry in the electric field in the spectrometer; the main retardation electrode could e.g. be cut in half to create a dipole field perpendicular to the magnetic field axis to

remove the stored electrons that cause the ionisation by an $E \times B$ drift. This dipole field could be applied periodically with a repetition rate well above the creation time of the ionisation.

- In general, the surface of the electrodes should be designed such that magnetic field lines are parallel to them. Wherever a magnetic field line crosses a material surface, the possibility exist that a charged particle will hit the surface when travelling along the field line. This solution has been implemented at KATRIN with great success [Valerius, 2009].
- An easy solution to avoid an unwanted trap is to install a wire in the centre of the trap that will absorb the electrons. This has been investigated in detail for the KATRIN experiment [Beck et al., 2010]. In that reference a more sophisticated version is discussed where a conductive wire periodically sweeps through an electron trap to remove electrons from it.

At WITCH a solution was chosen that led to the best result with a reasonable effort; a conductive wire was installed through the centre of the main retardation electrode. The effectiveness of this solution was measured during three measurements.

During the radioactive run in June 2010, performed to search for a good electron capture candidate, some recoil spectra were measured. The behaviour seen in these is as expected; larger retardation voltages lead to a lower count rate. However, due to the low absolute count rate, caused by the long half-life of the contaminants, one cannot draw solid conclusions. It might be that the γ intensity was too low to cause any ionisation effect, or that the build-up time was too long and thus not observed in the measurements.

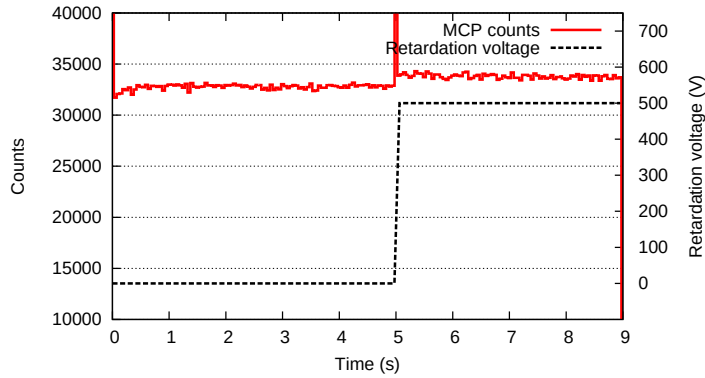


Figure 5.20 – Measurement of the ionisation created by a ^{137}Cs source in the decay trap. During the first 5 s the spectrometer is at 0 V, afterwards it is switched to 500 V.

Measurements – with the wire – were also performed with a radioactive source in the magnet bore tube – while the trap structure was not in the system. An

^{241}Am source with an intensity of $\sim 40\text{ kBq}$ did not cause any ionisation effects. Another test with a ^{137}Cs source with an activity of 2.7 MBq did not yield a zero result however, see figure 5.20. This figure should be compared with figure 5.6 where a similar measurement was performed with a $40\text{ kBq } ^{60}\text{Co}$ source. Even though an effect is still observed with ^{137}Cs this result is still encouraging. First of all, the intensity of the ^{137}Cs source is about ~ 70 times higher than the ^{60}Co source used before. Further, the observed difference in background ($\sim 5\%$ for ^{137}Cs versus $\sim 20\%$ for ^{60}Co) is significantly reduced. Secondly, the vacuum was far from good; it was in the 10^{-7} mbar range. Thirdly, the fact that some ionisation effect is still observed does not mean that the implemented solution of a conductive wire through the electron trap does not work; it may merely mean that the wire was not perfectly centred and that not all electrons were absorbed by the wire since it was not perfectly centred. It could easily have been of the order of 5 mm off centre.

5.5 Conclusion and Outlook

Based on electrons trapped in Penning-like traps the source of the ionisation processes at play in the WITCH setup have been identified thanks to simulations and measurements. All observed phenomena can be explained by primary electrons created in the upper part of the spectrometer that create secondary electrons in the main retardation electrode. These secondary electrons create further ion–electron pairs, of which the ions can be focussed onto the detector and contribute to the background count rate. These effects are now under control and should be removed completely in the very near future; nothing is hampering a first recoil ion energy spectrum from ^{35}Ar decay any longer.

For the future, first of all, a more permanent solution for the installation of the wire has to be foreseen. Important is that the wire traverses the centre of the main retardation electrode exactly so that all possible trapped electrons are absorbed. When this is done, the effectiveness of the implemented solution will again be tested with a radioactive source. This can be done with the same ^{137}Cs source of 2.7 MBq , or possibly with a ^{22}Na source of 3 MBq , which might become available. A β^+ source would be preferable as it approximates a ^{35}Ar source best. However, a β^+ source meeting all the constraints – i.e. an intensity of $\sim 1\text{ MBq}$, suited for vacuum, high magnetic fields and low temperatures (-50°C) – is not easy to obtain. An alternative for a β^+ source could be a γ source that exposes the same components of the setup to radiation as the β^+ source would do, with the same intensity. Simulations show that the β 's hit the system mostly in the einzel lens region; one could therefore try to place a source on top of one of the re-acceleration electrodes.

The next step is to investigate the effect of the wire on a recoil ion energy spectrum in detail. Obviously, some recoil ions will be absorbed by this conductive wire as well. If the probability for this is the same for all energies of the recoil ions, this will merely lead to a small reduction of statistics (i.e. about 4% [Friedag, 2012]). However, any energy dependence of this absorption effect

could possibly be fatal for the experiment. Other solutions have to be looked at in that case. Since the electrons are created in the einzel lens electrode and downstream, one can think of coating or treating the surfaces of these electrodes to reduce the electron yield. This will increase the build up time of an unwanted electron trap in the main retardation electrode, and in turn allow using a sweeping conductive wire that only clears away the electrons from the spectrometer every few seconds. During the measurement this sweeping wire can then be kept outside the path of the recoil ions.

Now that this final hurdle towards a measurement of a good-quality recoil ion energy spectrum in ^{35}Ar decay is overcome, one can start thinking of the data-analysis. In the next chapter the influence of systematic effects on a recoil ion energy spectrum will be discussed in terms of how they influence a precise extraction of a .

Chapter 6

Study of Systematic Effects

The determination of the β - ν angular correlation coefficient a at WITCH requires a precise measurement of the shape of the recoil ion energy spectrum. Any systematic effect that could change the shape of this spectrum has to be identified, modelled and taken into account during the data-analysis. Moreover, when aiming at a measurement of a with high precision – and thus with high measurement statistics – it is advantageous to focus on regions in the spectrum that are sensitive to deviations from the Standard Model. To enable this, it is imperative that all systematic effects and how they modify the shape of the recoil ion energy spectrum have been studied and can be taken into account. There can be two types of disturbances; the shape of the recoil ion energy spectrum can be changed in a ‘random’ way or more dangerously, the effect can modify the shape of the spectrum in the same way a non-Standard Model value of a would. The former will hamper a correct analysis of the spectrum, while the latter might be overlooked and lead to wrong conclusions about the value of a , and thus about potential scalar currents.

In this chapter the systematic effects which have been identified till now will be presented in a non-exhaustive list (section 6.1). The components from the WITCH setup involved, range from the source (the decay trap) until the detector. But also the analysis method has to be scrutinised. Where possible, the influence of these effects is quantified in terms of how they influence a . How this was simulated is explained in detail in appendix C. The summary of systematic effects will be followed by a recipe of how to investigate these effects. Measurements and simulations already performed in this respect will be presented to estimate their importance for a determination of a (section 6.3). The current status of the investigation of systematic effects will be summarised in section 6.4. Finally, this summary will be the basis for a discussion of which effects have to be investigated in more detail or how they can be reduced during a measurement, e.g. by using different measurement cycles.

6.1 Overview

Different parts of the setup are sensitive to different systematic effects. The list below is therefore arranged according to the different parts of the experiment. The properties of the radioactive ion cloud in the decay trap are important as this is the source of the experiment. The spectrometer is responsible for the transport and energy determination of the recoil ions. The efficiency of the detector surface is of course very important as well. Additionally, the shape of the spectrum is also influenced by effects not included in the standard weak interaction theory, that stem from electromagnetism or the strong interaction. Finally, the simulations assisting in the data-analysis need to be thoroughly checked for consistency and reproducibility. In the first section all effects will be listed and shortly discussed.

6.1.1 Source

The radioactive source in the WITCH experiment is an ion cloud confined in a Penning trap. Ion clouds with more than a few ions and less dense than plasmas are not very well understood yet and the equations of motion can not be solved analytically due to the many-particle nature of the problem. The phase space of the ion cloud, which is required as a starting point for particle tracking simulations, is thus also not exactly known. Moreover, it is not known what the time scale is for a change of the phase space distribution in the decay trap. For a relatively low number of ions ($N = 100\text{--}1000$), but at a low temperature ($T = 1\text{--}10\text{ mK}$), a collective motion of the ion cloud has been shown [Dubin & O’Neil, 1988]. Since the ion cloud in the decay trap is first prepared in the cooler trap, also this trap has to be investigated in detail. Settings such as the trap depth, the buffer gas pressure and the cooling time in the cooler trap all influence the properties of the final source and thus have to be well-optimised and under control. This requires detailed simulations [Van Gorp et al., 2011], measurements and (technical) optimisation [Van Gorp, 2011]. The precise characterisation of the WITCH ion cloud is still in its early stages.

Space distribution

The spatial distribution of the ion cloud is determined by several effects like

- The behaviour of an ion cloud in equilibrium and how this is affected by the Coulomb interaction between the stored ions.
- The preparation of the ion cloud; i.e. the cooling of the cloud and the transfer from the cooler to the decay trap. The maximum initial radius of the ion cloud in the decay trap is given by the size of the pumping diaphragm, typically 2–3 mm.
- The stability of the power supplies delivering the voltages for the traps.

- How well the actual traps approximate an ideal trap; i.e. mechanical imperfections and alignment of the magnetic and electric field. The WITCH Penning traps are cylindrical traps and thus only realise the proper quadrupolar Penning trap potential in a small area around the centre of the trap; the radius of this area is about 1 cm and the axial length about 4 cm in total [Raimbault-Hartmann et al., 1997].
- ...

In principle, the size of the ion cloud is not important as long as all recoil ions end up on the detector surface and the detector has a homogeneous detection efficiency. Ions not ending up on the detector will distort the recoil ion energy spectrum, especially if the focussing onto the detector is energy dependent. Fortunately, after the installation of a new detector with an active surface with a diameter of 8 cm (compared to 4 cm previously), this is not an issue anymore [Friedag, 2012].

Starting position of a recoil ion

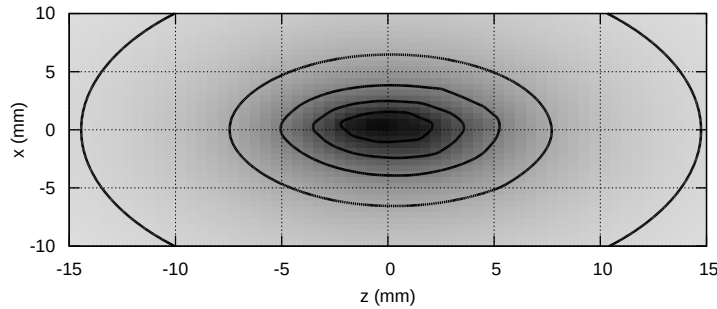


Figure 6.1 – Coulomb potential generated by a cloud of 10^6 ions; shown is a cross section of the trap potential (i.e. the $y = 0$ plane), with z parallel to the magnetic field axis and $x = y = z = 0$ the decay trap centre. The position of the ions is assumed to follow a Gaussian distribution with a standard deviation of $\sqrt{2}$ mm for the radius and a standard deviation of $\sqrt{7}$ mm axially. The inner contour corresponds to 0.50 V and the outer contour corresponds to 0.10 V. Each contour represents a step of 0.10 V. The distribution depicted here was used for the simulations shown in figure 6.2. Assuming that the spatial distribution of the ions remains the same, the Coulomb potential scales linearly with the number of ions.

The starting position of a recoil ion, however, needs to be taken into account in the particle tracking simulations for several reasons;

- The potential in the trap at which the recoil ion is created will change its measured recoil energy. For a trap depth of 1 V this will only cause a shift smaller than 0.05 eV (0.012 eV) for ions 1 cm (0.5 cm) axially away from the trap centre, and can thus be neglected. This effect becomes important – if not properly taken into account – for trap potentials deviating more than 0.1 V from the potential at the centre which changes a by $\sim 0.3\%$ maximally (figure 6.6).
- The same effect is present for the potential created by the ion cloud itself, see figure 6.1 and figure 6.2. For a low number of ions (i.e. $< 5 \cdot 10^4$ ions per trap load) the Coulomb potential generated by the ions can be neglected in the data-analysis as the maximum potential generated by $5 \cdot 10^4$ ions is ~ 0.025 V for the position distribution shown in figure 6.1. However, for the intended number of ions in the trap (i.e. 10^6 ions per trap load) a potential of ~ 0.5 V is generated in the trap centre, which is significant. The effect can be taken into account, by good knowledge about the number of ions in the trap and their spatial distribution. However, deviations of 10^5 ions in the estimation of the ion number (i.e. a 10 % uncertainty for 10^6 ions) can already cause a small deviation in the determination of a , by 0.15 %. Note that it is not the relative uncertainty on the number of ions that is important, but the absolute uncertainty.
- The potentials created by the cylindrical trap electrodes are not constant from the electrode surface ($r = 20$ mm) to the centre of the electrode ($r = 0$ mm). Due to this the ion will see a different potential in the endcap region depending on the radius (with respect to the centre) it is on. For a trap depth of 1 V, this difference is 1.5 mV in the upper endcap electrode from the decay trap (DEE6); this effect can be neglected in the extraction of a value for a (see figure 6.5).
- The argument about the potentials from the previous item is applicable to the retardation spectrometer as well. For an applied voltage of 500 V the difference between the centre and the wall of the electrode is 1.01 V [Delaure, 2004]. Therefore the radial starting position has to be taken into account in the particle tracking simulations. Neglecting this can cause deviations in a larger than 1 % (see figure 6.6). Also the axial starting position has to be taken into account [Friedag, 2008]. The phase of the ions' cyclotron motion will depend on the axial starting position, and so will then also the retardation potential they encounter. In Ref. [Delaure, 2004] an example is given for ^{26}mAl ; with a cyclotron radius of 14 mm the difference can be as large as 0.2 V if the centre of the cyclotron motion is radially ~ 70 mm away from the axis of the retardation electrode.
- Finally, also the exact magnetic field at the starting position is in principle important for a correct determination of the cut-off angle [Friedag, 2008]. The magnetic field decreases slightly from the decay trap centre to the centre of the upper endcap electrode (DEE6); some of the radial kinetic energy will have been converted into axial kinetic energy already over this distance. However, for ions not moving away from the trap centre by more

than 4 cm in the axial direction – which is certainly the case – this effect can be neglected as the ratio between the magnetic fields at the centre and at 4 cm is 1.000087, which does not disturb the extraction of a (see figure 6.7).

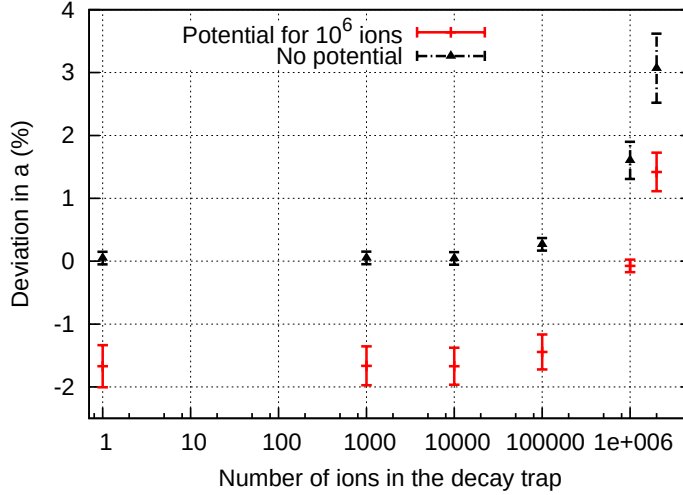


Figure 6.2 – Deviation in the determination of a due to the Coulomb potential generated by the ions in the cloud. If the effect of this potential is ignored, the data points labelled ‘No potential’ show how this would influence the extraction of a , as a function of the actual numbers of ions in the cloud. Obviously, the effect should and can be taken into account; this is what is shown by the data points labelled by ‘Potential for 10^6 ions’, again as a function of the number of ions in the cloud where it is assumed in the data-analysis that there are 10^6 ions in the ion cloud. See figure 6.1 for the distribution used. For this an ion cloud is assumed where the spatial distribution follows a Gaussian distribution around the trap centre; the standard deviation of the radius is taken to be $\sqrt{2}$ mm and the standard deviation is $\sqrt{7}$ mm axially.

To correctly take these effects into account, the spatial distribution and the number of ions in the cloud need to be known precisely.

Energy distribution

Any kinetic energy the radioactive ions possess at the instant of their decay will contribute to the recoil ion energy – due to thermal Doppler broadening. To take this effect into account in the data-analysis one needs to precisely know the energy distribution of the radioactive source. The ions are cooled with a buffer gas at room temperature, which will give them a Maxwell-Boltzmann energy distribution with two degrees of freedom and with a mean energy of $E =$

$k_B T \approx 25$ meV [Brown & Gabrielse, 1986]. This distribution can be altered during the transfer from the cooler to the decay trap.

The effect of the energy distribution on the recoil ion energy spectrum has been investigated in detail in previous WITCH theses [Delauré, 2004, Kozlov, 2005, Coeck, 2007]. It can be summarised as a smearing out of the spectrum where the recoil energy is changed from E_r to $(\sqrt{E_r} + \sqrt{E_{\text{ion}}})^2 = E_r + E_{\text{ion}} + 2\sqrt{E_r \cdot E_{\text{ion}}}$, with E_{ion} the kinetic energy of the ion prior to the decay.

Although the induced change in spectrum shape does not mimic a non-Standard Model value of a , it will induce systematic uncertainties on the final result. The energy spectrum will span a broader energy range which will lead to a worse signal-to-noise ratio for the entire spectrum. In Fig. 6.3 the influence of the temperature is shown, assuming a Maxwell-Boltzmann energy distribution for a temperature of 293 K, i.e. room temperature. For temperatures from 150 K to 600 K the deviations from the assumed value of a do not deviate more than 0.5 % within one standard deviation. This corresponds to a wrong determination of the temperature by a factor of two, which is rather large already.

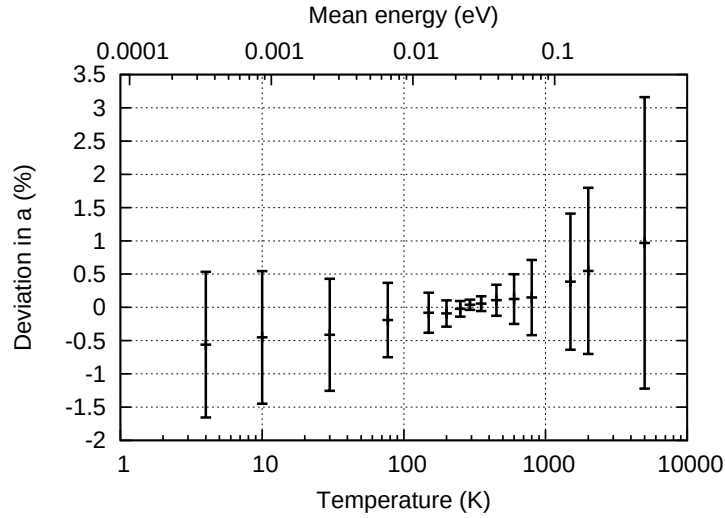


Figure 6.3 – Deviation in the determination of a caused by a wrong determination of the temperature of the ion cloud, assuming that the ion cloud has a temperature of 293 K (25.25 meV) in a Maxwell-Boltzmann energy distribution with three degrees of freedom. The upper x-axis gives the mean energy of the distribution according to $E = k_B T$.

Change of phase space

Once the ion cloud is trapped in the decay trap it is *a priori* not certain that the phase space distribution will remain constant. Changes can stem from the inherent motion of the ion cloud in a Penning trap, but clearly also the

radioactive decay will change the phase space of the cloud.

The first fundamental problem to solve in this respect is whether an ion cloud containing 10^4 – 10^6 particles remains unchanged after the transfer from the cooler trap to the decay trap and whether there are no losses. Changes can be caused by physical effects – e.g. the onset of collective motion, the Coulomb potential the ions feel, collisions with or scattering on rest gas (or other ions) –, but it can also be induced by the electronics like ripples in the power supplies. If these ripples have a frequency close to one of the resonant frequencies (e.g. ω_- , ω_+ , ω_z , or a sideband, e.g. $\omega_- + \omega_+$), the ion cloud will be strongly influenced indeed.

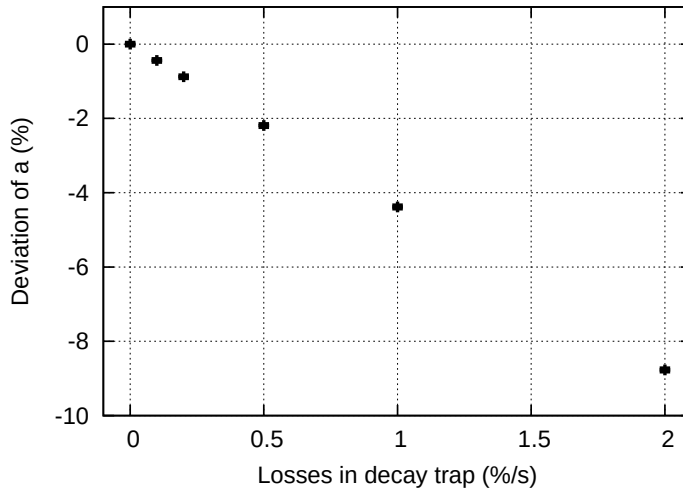


Figure 6.4 – Deviation in the determination of a for ^{35}Ar due to losses in the decay trap. For this a measurement cycle was assumed where the retardation voltage is ramped from 0 V to 500 V in 2.5 s. The current upper limit, from a non-dedicated measurement, is 2.6 % losses per second at a confidence level of 99.5 % [Beck et al., 2011].

More drastically, ion losses from the decay trap can be present. The effect of this on a correct determination of a is given in figure 6.4. For an experimental cycle where the retardation spectrometer voltage is ramped from 0 V to 500 V in 2.5 s, the effect of ion losses from the decay trap is significant. Under the assumption that there are no ion losses from the decay trap, losses of only 0.1 %/s will already shift the extracted value for a with 0.5 %. To avoid a misinterpretation of the spectrum shape, these losses have to be measured precisely or the experimental cycle needs to be changed; i.e. if the retardation voltage during one experimental cycle is constant, trap losses have a negligible influence.

An important change in phase space – if not the most important one – will be caused by the radioactive decay and the corresponding escape of ions from the decay trap. The number of ions in the decay trap will obviously decrease due to

the recoiling ions. As such the Coulomb interactions within the ion cloud can change, which can lead to a reconfiguration of the spatial and energy distribution in the ion cloud. Additionally it might be possible that the distributions in the ion cloud are modified by recoiling ions passing close to another ion.

But even without performing simulations an obvious example of how the radioactive decay influences the ion cloud can be found. Ions will decay and as such the Coulomb potential generated by the ions will change, and this will in turn modify the starting potential of the ions (see section 6.1.1). Assume that an ion cloud obeys a Gaussian distribution with a standard deviation of $\sqrt{2}$ mm for the radius and $\sqrt{7}$ mm axially. For 10^6 ions a potential of ~ 0.6 V will be generated in the centre of the cloud. After two half-lives of the radioactive ions, only $2.5 \cdot 10^5$ ions will be left, which results in a potential of ~ 0.15 V in the cloud centre. This definitely needs to be taken into account in the data-analysis (see figure 6.6).

A Penning trap as a radioactive source

Using a Penning trap as a radioactive source container provides an environment from which the recoil ions can leave mostly undisturbed and without significant energy losses, but obviously the magnetic and electric fields will influence the recoil ions. This has some benefits, like focussing due to the magnetic field, but also some disadvantages. Ions can for instance stay trapped in the decay trap when their axial energy is not sufficient to allow them to overcome the decay trap endcap voltage barrier. A maximum angle and minimum energy is required for this. The so-called cut-off angle θ_c – with respect to the magnetic field axis – is defined as the maximum angle for the velocity of a recoil ion to pass the endcaps and escape the trap;

$$\theta_c = \arccos \sqrt{\frac{eU_C}{T_r} \frac{B_i}{B_f}} \quad , \quad (6.1)$$

with e the charge of the ion, U_C the voltage between the endcap and the bottom of the trap, T_r the recoil energy of the ions, and B_i and B_f the magnetic field at the starting position of the recoil ion and at the decay trap endcap electrode, respectively. Note that $B_f < B_0$. This effect is taken into account in the tracking simulations and has been investigated already [Friedag, 2008, Friedag, 2012]. The factor $\frac{B_i}{B_f}$ has to be included because the magnetic field is lower at the endcap electrode than in the trap centre, and thus some of the radial kinetic energy has already been converted into axial kinetic energy. The cut-off angle will change for different starting positions of the ions, this has been discussed already in section 6.1.1. The most general form of equation 6.1 will have to include a radial dependence in the endcap voltage U_c and a position dependence in the starting magnetic field B_i :

$$\theta_c = \arccos \sqrt{\frac{eU_C(r)}{T_r} \frac{B_i(r, z)}{B_f(r)}} \quad , \quad (6.2)$$

where $U_C(r)$ is now defined as the potential difference between the starting position of the ion and the potential where it crosses the endcap electrode.

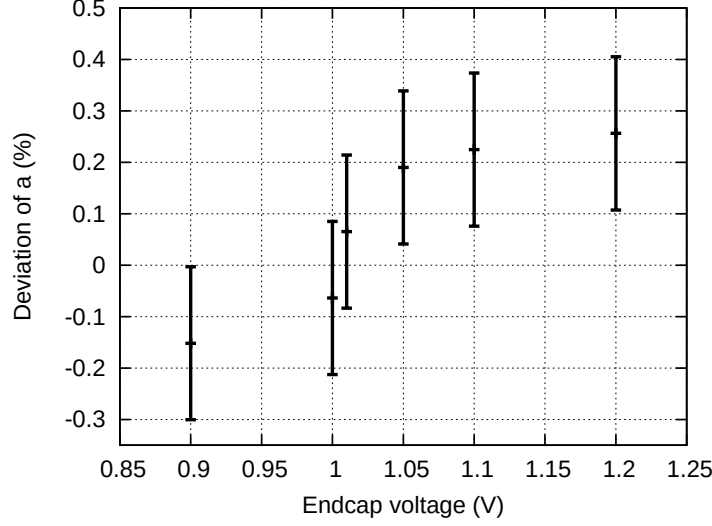


Figure 6.5 – Deviation in the determination of a for different endcap voltages, assuming a nominal endcap voltage of 1 V. Note that deviations of 0.1 % lie within the statistical fluctuations of the generated spectra. The power supply in use has a precision of 10 mV, corresponding to 1.01 V in this case.

In this respect the voltage on the upper endcap electrode in the decay trap is important; inaccuracies of the power supply will give a wrong value for U_C in Eq. 6.1 and thus lead to an incorrect extraction of a . In figure 6.5 the effect of a different endcap value on a is shown. It follows that this does not affect a correct determination of a within the current precision of the power supply.

6.1.2 Spectrometer

The spectrometer is the energy filter of the experiment and it also takes care of the transport of recoil ions from the traps to the detector. Different systematic errors relate to those two functions. Also background signals (i.e. noise or ionisation effects) can be generated by the spectrometer.

Background

Unfortunately the spectrometer can be the source of extra background, such as ions created in it, of which dramatic examples were shown already in chapter 5. Other processes can also lead to an increased background signal. Three possibilities are considered at this point:

- Neutral particles are not affected by the magnetic and electric fields and can wander freely in the system. Recoil atoms (instead of recoil ions) can end up on the detector and be detected although with a strongly reduced efficiency. Since they have a rather high energy compared to the rest gas atoms they could, in addition, cause some extra ionisation. Also radioactive ions that are neutralised in the traps can contribute to an increased background signal as they can go around freely in the system like the rest gas.
- Recoil ions that have insufficient energy to pass the barrier in the spectrometer could be stored in the spectrometer. This could lead to distortions of the potential in the spectrometer, or in turn create ionisation.
- Radioactive ions that have not been trapped or have been lost from the traps can decay somewhere else in the system.

An increased background count rate which is constant over the entire spectrum will cause the statistical uncertainty on a to increase. However, a background signal that is not constant in time or dependent on the retardation voltage will cause a misinterpretation of the spectrum. Examples of this are given in section 5.3.4. The effect on a can be estimated from figure 6.4. Ion losses from the decay trap of 0.1 %/s cause a deviation of a of 0.5 %. The former corresponds to a decreased count rate of 0.25 % at 500 V. This corresponds in turn to a difference in background between a retardation voltage of 0 V and 500 V of 2.5 background events per 1000 recoil ions are detected at 500 V. The effect observed during the ^{35}Ar run of 2009 (see figure 5.8) thus has to be reduced by several orders of magnitude.

Transport

The transport from the decay trap to the detector is in principle straightforward and is calculated by tracking simulations [Friedag, 2008, Mader, 2010, Friedag, 2012]. However, several effects can cause disturbances:

- Scattering of recoil ions with the rest gas can change the transport of the ions, but it can also lead to a false energy signature. This has already been investigated in Ref. [Delauré, 2004]. The effect on the response function of a Stokes damping force acting on the recoil ions was simulated there; pressures lower than 10^{-6} mbar in the spectrometer volume do not adversely influence the response function and the determination of a . The scattering of recoil ions is currently being further investigated by using realistic ion–rest gas collisions [Friedag, 2012].
- Potential transmission losses have to be taken into account. This depends mainly on the re-acceleration potentials and the size of the detector. This effect is included in the tracking simulations [Friedag, 2012].
- The focussing on the detector has to be simulated correctly. The main worry is that energy-dependent effects in combination with an inhomoge-

neous detection efficiency can lead to distortions of the spectrum shape [Friedag, 2012]. The effect of a random inhomogeneous detection efficiency over the detector surface is discussed in section 5.8.

Also some effects or insufficient knowledge about certain aspects of the system, make the interpretation of the tracking simulations more difficult;

- Asymmetric elements, like mounting structures, the diagnostic MCP in the spectrometer or the conductive wire to avoid ionisation, are at present hard to model correctly in the tracking simulations since these assume cylindrical symmetry for the calculation of the electromagnetic fields and the tracking of the particles.
- Deviations of the shape of the used electrodes from cylindrical symmetry.
- A potential misalignment of the electric and magnetic field has to be measured in order to be included in the simulations (see e.g. alignment measurement in [Beck et al., 2011]).
- The exact magnetic field map needs to be known, and more precisely: the distance between the centres of the two superconducting magnets. This can be measured based on the data provided by the magnet manufacturer.

To check and quantify several of the above-mentioned effects, the transmission function of a well-controlled source should be measured and verified by simulations. The perfect source for this are mono-energetic recoil ions coming from electron capture decay since they will result in a peak in the recoil spectrum (due to two-body decay). Excited ions from the trap – radially or axially – could also be used, as well as a dedicated measurement with an ion source in the decay trap. If the measured transmission function can be reproduced with good precision, one is certain that the important systematic effects have been identified and one can rely on the ability of the tracking simulations to accurately reproduce the transport through the spectrometer.

Energy Filter

The potential in the analysis plane of the retardation spectrometer is crucial for the energy determination of recoil ions. The way this voltage is applied can lead to some systematic uncertainties. First of all the precision and accuracy of the power supply needs to be good, see figure 6.6, and obviously the stability in time or within a certain temperature range needs to be taken into account as well. A shift in the retardation potential of 0.2 % leads to a shift in a of ~ 0.5 %. This problem can be circumvented by allowing for a shift in energy when fitting the spectrum shape. The precision of the power supply is less critical it seems (see figure 6.6), under the assumption that deviations from the applied value are distributed according to a Gaussian function where the precision of the power supply is the standard deviation. The precision was assumed to be constant for all voltages. The impact on the determination of a

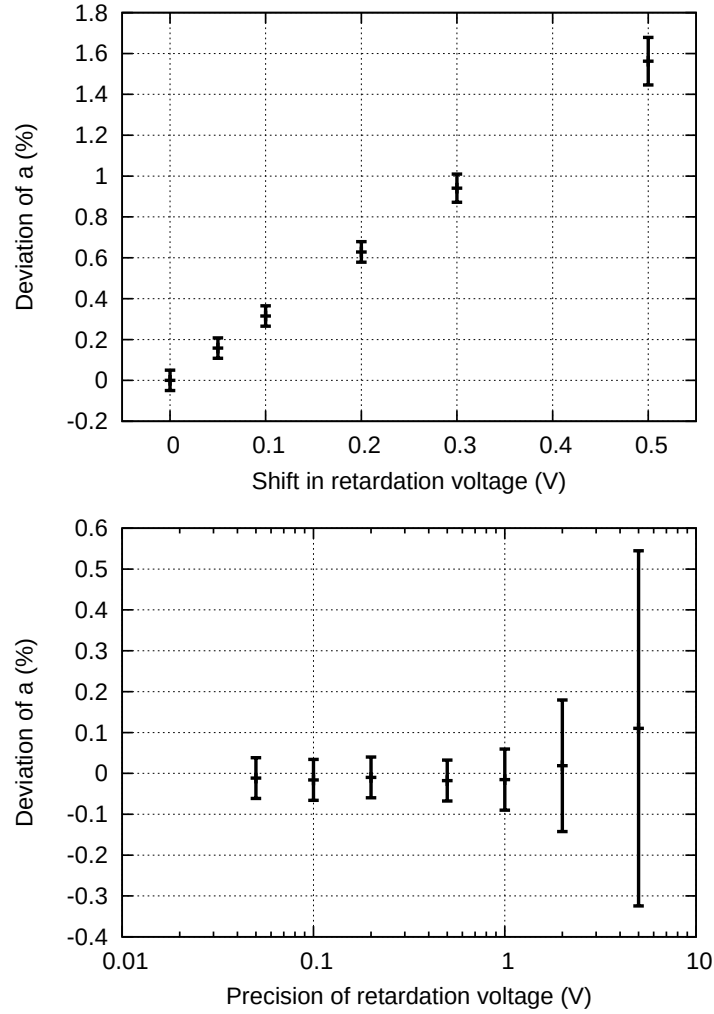


Figure 6.6 – Top: Deviation in the determination of a for a shift in the retardation voltage. The precision of the current retardation supply is 0.1 % within $100\mu\text{s}$ after applying the voltage, while the final precision is $50\mu\text{V}$. **Bottom:** The effect of the precision of the power supply. These simulations were done with 1 V bins. The precision of the power supply was modelled by assuming that the applied voltage can deviate from the set voltage according to a Gaussian distribution where the standard deviation is the precision of the power supply.

is found to be negligible. However, a more accurate model of the precision of a power supply might be necessary. The accuracy/precision of the retardation power supply used in previous measurements was about 0.1 %, while the new retardation power supply reaches the same accuracy/precision after $100\,\mu\text{s}$ and reaches a final accuracy/precision of $50\,\mu\text{V}$.

Secondly, the measurement cycle has to be taken into account. If the voltage is ramped from 0 V to a maximum value during one experimental cycle, the rise time of the power supply is important. Data taken when the spectrometer is changing voltage are in principle not very reliable and should be discarded, which leads to a small loss in statistics. Besides the more technical issues, for a correct measurement of the energy the exact applied potential needs to be known (see e.g. section 6.3.2) together with the ratio of the magnetic field in the decay trap and in the spectrometer (see figure 6.7). The magnetic field ratio needs to be known with a precision of 2 % to extract a correctly within 0.2 %, which does not pose a problem at present (see section 6.3.2).

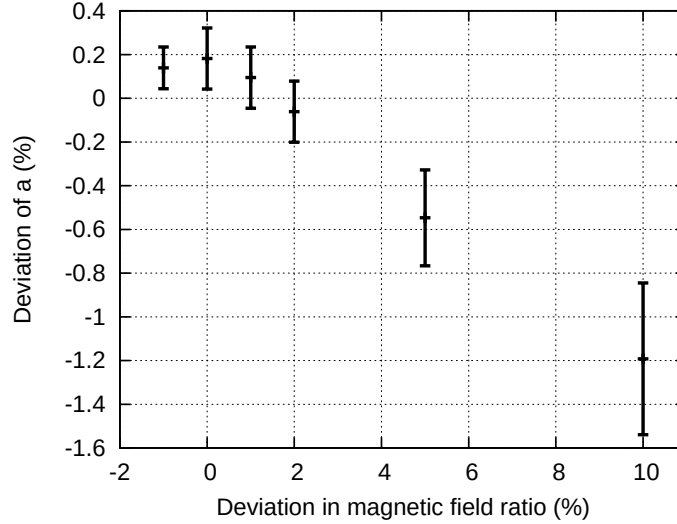


Figure 6.7 – Deviation in the determination of a for an incorrect determination of the ratio of the high field (in the decay trap) and the low field (the analysis plane in the retardation spectrometer). The assumed ratio is 0.1 T/6 T or 1.67 %, which corresponds to a deviation of 0 % in the graph. The deviation of a of the point at 0 % is due to statistical fluctuations in the generated spectra; the spectra for the different ratios were all created independently.

6.1.3 Detector

For ions that have reached the detector surface there is still no guarantee that they will be detected with an efficiency of 100 %. Since the current detector is

a DLD80 MCP from RöntDek (see section 2.5), effects related to this detector type will be discussed first, while more general detector effects will be considered thereafter.

MCP effects

A detector of the same type as the WITCH MCP detector has been studied thoroughly in Ref. [Liénard et al., 2005]. Its efficiency of 52.3(3) % is determined by the ratio of the channel aperture surface to the active surface. The energy and angular dependence of the efficiency are not a problem due to the re-acceleration of the ions; they all arrive with a high energy ($O(10\text{ keV})$) due to the detector potential and because of this they also arrive at just a small angle with respect to the normal to the detection surface. However, the efficiency of the detector is not necessarily homogeneous over its entire surface. This issue was already raised during the analysis of the ^{124}In data and has later proven to be an issue during the run of June 2010. This can be caused by the MCP itself, if certain channels are damaged, but it can also be due to a reduced efficiency of the delay lines. The former effect reduces the efficiency of a certain area of the detection surface and is a known degradation effect of MCPs. The latter is not a commonly observed effect and will not affect the efficiency of the MCP itself. However, it can lead to a wrong characterisation of the efficiency of the detection surface and thereby influence the data-analysis. The effect of an inhomogeneous detection efficiency was simulated; for details see section C.3.2. If the fluctuations of the detection efficiency are randomly distributed over the detector surface – in steps of 1 mm –, no influence on the determination of a can be found. This is even so when these fluctuations would be as large as 10 %; in reality the fluctuations in efficiency are about 1 % from the mean [Liénard et al., 2005]. Whether or not these are random is not clear from that reference. This can be easily understood, even if the focussing of the recoil ions is energy dependent. A reduced detection efficiency at some spot on the detector will be compensated on average by an increased detection efficiency at another spot of the detector, but at the same radius, if it is random.

The situation changes when the inhomogeneities in the detection efficiency are not randomly distributed. For instance, if the detection efficiency is reduced in the centre this will reduce the count rate for the low-energy recoil ions as recoil ions with a higher energy end up on average on a larger radius of the detector. This can be estimated from figure 6.4. Ions at 50 eV end up within a radius of 1 cm of the detector, while 450 eV recoil ions end up within 3 cm, for a retardation voltage of 0 V. A difference in detection efficiency of 1 % for the regions inside and outside a radius of 2 cm could already lead to a deviation in a of 2 %. A characterisation of the detection efficiency over the detector surface is therefore essential.

General effects

On top of the MCP-specific effects there are some systematic effects which need to be taken into account for any detector:

- The precise dimensions and position of the detection surface are important for the tracking simulations during data-analysis. Especially the axial position is crucial as changes there will lead to different focussing onto the detector. The influence of the axial position of the detector on the focussing of the ions has been investigated already in Ref. [Mader, 2010]. Small shifts in the radial direction should not influence the spectrum as it can be checked whether the beamspot of the recoil ions lies fully on the detector surface during an experiment.
- The β background will add to the background counts in a spectrum and thus increase the statistical uncertainty on the determination of a . The detection of β 's cannot be avoided with an MCP detector, but the use of another type of detector, e.g. a solid state detector, could reduce this effect. A small fraction of the β spectrum will contribute to the background of the recoil ion energy spectrum with a solid state detector, while the full β spectrum contributes the recoil ion energy spectrum with an MCP detector – be it at a reduced efficiency compared to the detection of ions.

6.1.4 Theory

Any measurement of the β - ν correlation (or another correlation) is subject to corrections to first-order Standard Model predictions. These modifications will be listed after a short description of the shake-off effects and the resulting charge state distribution.

Charge state distribution

Normally a 1^+ ion undergoing β^- decay will emerge as a 2^+ daughter ion. For β^+ decay the daughter will be neutral. However, due to the shake-off effect it is possible that one or more electrons are ejected from the ion/atom. This is caused by the sudden change of nuclear charge. For light nuclei this can also be caused by the sudden change in momentum. Moreover, if the daughter nucleus ends up in an excited state electrons from the inner shells can be kicked out due to internal conversion. The subsequent Auger cascade can then release more electrons. Thus, the daughter products of β -decaying 1^+ ions will have a charge state distribution, with 2^+ (0) being the predominant charge state for β^- (β^+) decay. For electron capture decays, the ejection of electrons due to an Auger cascade will be the main effect, resulting in a charge state distribution with higher charges.

The charge state distribution will not lead to systematic errors in itself if one only uses the upper part of the recoil ion energy spectrum that constrains only

the lowest charge state; higher charge states will end up in a lower-energy part of the spectrum. Using the retardation spectrometer, the endpoint of the energy spectrum from a charged ion is located at $U = E_r/q$, with U the retardation voltage, E_r the endpoint energy and q the charge state of the ion expressed in elementary charges. However, if the charge state distribution after the decay would be precisely known, 50–100 % in statistics can be gained, depending on the isotope used; e.g. for ^{35}Ar this would be $\sim 60\%$ and for ^{124}In 100 % or more could be gained. The measurement of the charge state distribution at WITCH is not straightforward. A time-of-flight technique where the decay products are stored in the decay trap and ejected afterwards, does not provide enough discrimination between the charge states [Nandi, 2007]. The same can be done for the cooler trap. The charge states will be distinguishable from one another, but higher charge states can be lost due to neutralisation.

The measurement of the charge state distribution is easier in a β - ν correlation experiment based on coincident detection of β 's and ions. It is planned to measure the charge state distribution after ^{35}Ar decay with the LPCTrap setup at GANIL which is at present the only ion trap that can perform this measurement. A measurement of the charge state distribution after ^6He decay has been performed already [Liénard et al., 2011]. Also in MOT-based experiments the charge state distribution after the decay has been observed [Scielzo et al., 2003].

Corrections to the spectrum shape

The extraction of a correct value or limit on exotic currents from a , requires some theoretical effects to be taken into account. First it has to be noted that a description of the weak interaction usually involves only first-order terms; i.e. the classification into Fermi and Gamow–Teller decays. But for precision measurements other effects – that are part of the Standard Electroweak Model and can be calculated – should be considered as well. The second (and lower) order effects will change the value of a , while they do not contribute to exotic currents in pure weak interaction effects.

- Radiative corrections take into account higher-order Feynman diagrams. For most decays this correction is at the 10^{-3} – 10^{-4} level and at the current precision not relevant yet. For the superallowed decay of ^{32}Ar the difference in a when taking into account the radiative corrections is 0.36 % [Glück, 1998]. Radiative corrections can be calculated for ^{35}Ar as well and have to be included for a detailed analysis the data in terms of possible new types of weak currents.
- Recoil corrections are admixtures of the strong interaction – i.e. interactions between the quarks in the decaying nucleon – into the weak interaction. These can be calculated and measured, but for fast transitions they are less important. For ^{35}Ar weak magnetism is the dominant term, but only shifts the value for a with -0.044% [De Leebeeck et al., 2011]. This is far smaller than the current experimental precision.

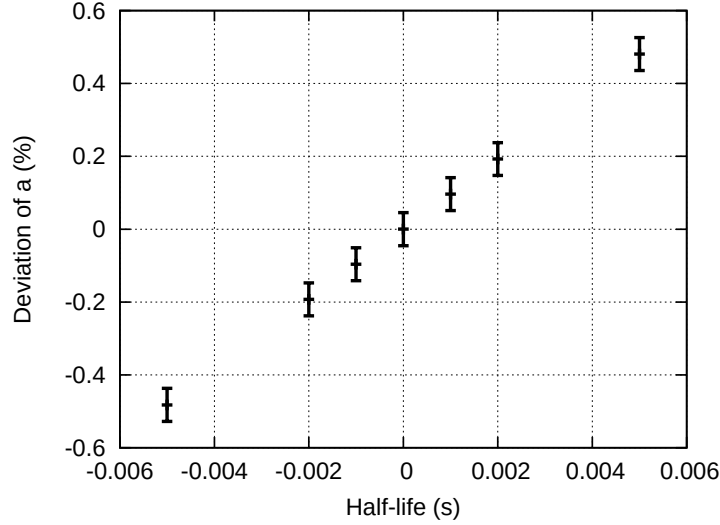


Figure 6.8 – Deviation in the determination of a for ^{35}Ar due to a wrong assumption for the half-life; the literature value is $1.7752(10)$ [Severijns et al., 2008]. For this a measurement cycle was assumed where the retardation voltage is ramped from 0 V to 500 V in 2.5 s.

- The mixing ratio ρ is the ratio between Fermi and Gamow–Teller decays in a nucleus. The value of a depends directly on this mixing ratio. Imprecise values for the mixing ratio will lead to wrong conclusions about exotic weak currents. For pure Fermi or Gamow–Teller decays this is of course not a problem, but for the mixed decay of ^{35}Ar (and the other mirror nuclei), this needs to be taken into account. For ^{35}Ar the mixing ratio ρ is $-0.2841(25)$ [Severijns et al., 2008]. The value for a – in the first-order approximation – is $0.9004(16)$, which has a relative uncertainty of 0.18 %. This is lower than the current experimental precision, which is necessary to constrain exotic currents in the Standard Model.
- Depending on the experimental cycle, a correct extraction of a also requires the half-life to be known precisely. Slightly different values for the half-life can lead to different results. The adopted half-life of ^{35}Ar is $1.7752(10)$ s [Severijns et al., 2008]. Dependence of a on the half-life can be avoided by doing a measurement with a constant retardation voltage during one experimental cycle. However, this requires a good normalisation method (see section 4.2.3). Deviations in a caused by a wrong knowledge of the half-life are shown in figure 6.8. A half-life that is off by 0.28 % induces a shift of a of ~ 0.5 %.
- Details of the decay are also important. If after the β decay the daughter ion ends up in an excited state, this will influence the recoil ion energy spectrum in two ways. First of all the recoil energy will be reduced and secondly the daughter ion will get an additional recoil kick due to de-

excitation via γ emission or internal conversion. The decay scheme of ^{35}Ar is shown in Fig. E.1.

6.1.5 Simulations

Finally all of the above mentioned effects need to be combined into one simulation routine taking care of the behaviour of the ions in the source and another routine for particle tracking and analysis. The latter is realised by the development of SimWITCH [Friedag, 2008, Mader, 2010, Friedag, 2012]; a Monte-Carlo routine taking into account the entire geometry of WITCH, based on a tracking routine for electrons developed for KATRIN [Glück, 2010]. The simulations of the source are performed with the Simbuca code [Van Gorp et al., 2011]. As such, the routines themselves should be the topic of a thorough investigation. Their reliability should be tested comparing simulation results with measurements performed in well-controlled experimental conditions.

Other inaccuracies that can enter into the simulations can be caused by an incomplete knowledge of the system properties, e.g. the position of all electrodes in the system needs to be known to good precision as is the case for the alignment of the magnetic and electric fields. Also, asymmetries in the system (e.g. the conductive wire to remove ionisation) need to be modelled sufficiently well (see Ref. [Friedag, 2012]). A measurement with a source in well-controlled conditions is necessary to validate the precision of the tracking simulations.

Since the simulations should not limit the final uncertainty of the result, the many tracking simulations that will be required need to be run with high statistics. To minimise the impact on the statistical uncertainty, they should contain 5 to 10 times more events than the measured spectrum. To correctly quantify the systematic uncertainties, these have to be estimated by allowing small variations in the parameters of the system, which requires many simulations. To this end it would be beneficial to optimise the simulation code so as to reduce the required computation time. New computational techniques like using a graphics processor instead of the central processor of a computer can increase the parallelism of the calculations [Van Gorp et al., 2011]. Faster integration methods can also reduce the computing time significantly.

6.2 Methodology

In this section a flow chart is given of how the investigation of a systematic effect typically proceeds.

1. Systematic effects have to be simulated based on basic assumptions. This shows how a certain effect will modify the recoil spectrum and whether it is a potential problem or not.
2. A measurement is performed to study the systematic effect in detail. In an ideal case this would be done with a radioactive beam, but often it is

more practical to have a well-controlled source which allows to focus on one particular effect. Measurements will have to confirm the correctness of the simulations and in turn the simulations will provide some insights that are not accessible by measurements.

3. Depending on the magnitude of the systematic effect one can continue to step 4 if it is not significant, or one has to go back to step 1 if the effect is significant and potentially problematic. In that case one has to think how to reduce the magnitude of the systematic effect by technical innovations. This is done in conjunction with simulations.
4. Finally, when the effect is reduced as much as possible, the remaining effect has to be modelled accurately to be included in the data-analysis procedure.

A dedicated campaign to identify and model systematic effects has not been started yet. Until now the focus was on the measurement of an ^{35}Ar recoil ion energy spectrum to extract a value for a . Of course, many test measurements have been performed over the years which will be presented in the next section. Also, some proposed effects have been simulated and investigated already without experimental corroboration. These are discussed in the next section.

6.3 Measurements and Simulations

In this section results regarding systematic effects for the measurement of a recoil ion energy spectrum are presented.

6.3.1 Source Properties

Space distribution: Ion cloud axial size

The axial size of the ion cloud can be directly linked to the axial energy distribution of the ion cloud if the potential in the decay trap is precisely known. One must however distinguish between two axial sizes of the detector. There is the axial size at a certain moment, and the axial size averaged over the measurement time. An ion cloud can be 5 mm long axially, but the ion cloud can collectively oscillate in the harmonic well of the Penning trap. This latter oscillation has a frequency of $\omega_z = \mathcal{O}(10\text{ kHz})$ so that only the amplitude of the axial oscillation is important for a measurement. It is this axial length that can be linked to the energy distribution, while the inherent length of the ion cloud should be probed by simulations.

The measurement of the ion cloud's energy distribution is explained in section 6.3.1. In figure 6.11 an example of an energy distribution is shown for a trap depth of 5 V. An ion with an energy of 0.7 eV will have an oscillation amplitude of ~ 5.5 mm. From an energy distribution a distribution for the oscillation amplitudes can be derived.

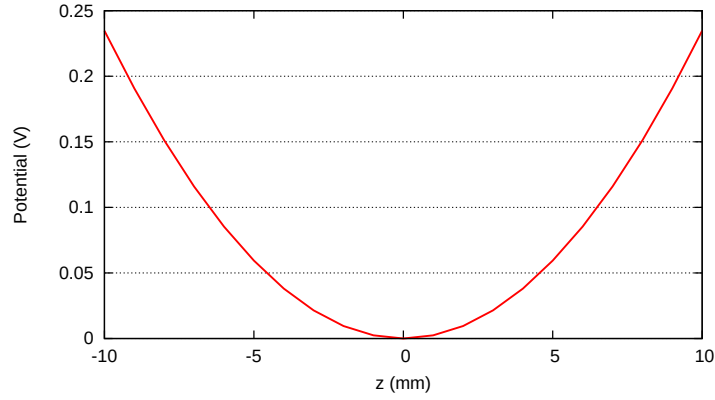


Figure 6.9 – The electric potential in the centre of the cooler trap on the symmetry axis for a trap depth of 5 V. An area of 2 cm centred around the trap centre is shown.

Space distribution: Ion cloud radial size

A good example of a systematic effect that has been studied by simulations and compared to experiment, is the radial ion cloud size. Tracking simulations were performed and compared to the experimental data of the ^{124}In run in 2006 [Mader, 2010] (Fig. 6.10). First the full width at half maximum (FWHM) of the detector spot (created by the recoil ions) was fitted from experimental data and found to be 4.50 ± 0.86 mm. Next the experiment was repeated in simulations – i.e. tracking recoil ions from the decay trap to the detector – for different ion cloud radii. Finally simulations were compared to experimental data. In this way the experimental detector spot size can be correlated to a certain ion cloud size in the decay trap, which yields the radial ion cloud size. Although the result of the analysis is not very precise, the radius of the ion cloud is estimated to lie between 1.7–4.3 mm. Another important result of this, besides a first determination of the ion cloud’s radius, is the fact that the recoil ions are all focussed onto the detector, since the FWHM of the detector spot is lower than 7 mm. If it would be higher than 7 mm some of the recoil ions would already miss the detector as can be seen in figure 6.10. For ion cloud radii larger than 5 mm the FWHM of the detector spot does not increase significantly anymore, which means that some recoil ions are missing the detector.

Energy distribution: Energy determination

The energy distribution of the ions in the cooler and decay traps can be determined. The ions are ejected from the trap into the spectrometer by lowering the voltage on an endcap electrode. The energy measurement is done by scanning the voltage on an endcap electrode or with the retardation spectrometer; both methods will give complementary information. The endcaps will probe

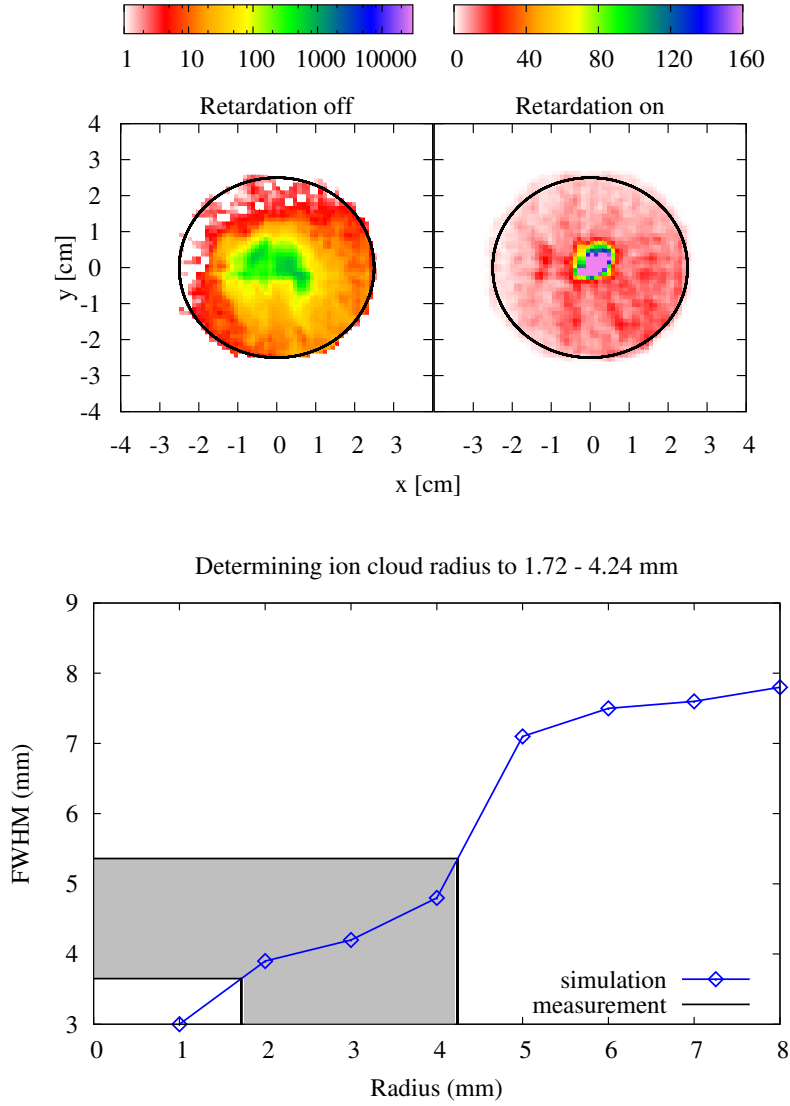


Figure 6.10 – The **top** panel shows the position information on the main MCP detector. To the left the combined signal from recoil ions and β 's is shown (retardation voltage at 0 V). To the right the ions that were shot over the decay trap (with an energy of 30 keV; central spot) along with the β background are depicted. The **bottom** panel compares the simulations with experiment. The gray area is the ion cloud size obtained from the measurement, while the blue line is the spot size determined as a function of the initial ion cloud size. This allows correlating the experimental spot size to a certain ion cloud size in the decay trap. Taken from [Mader, 2010, Beck et al., 2011].

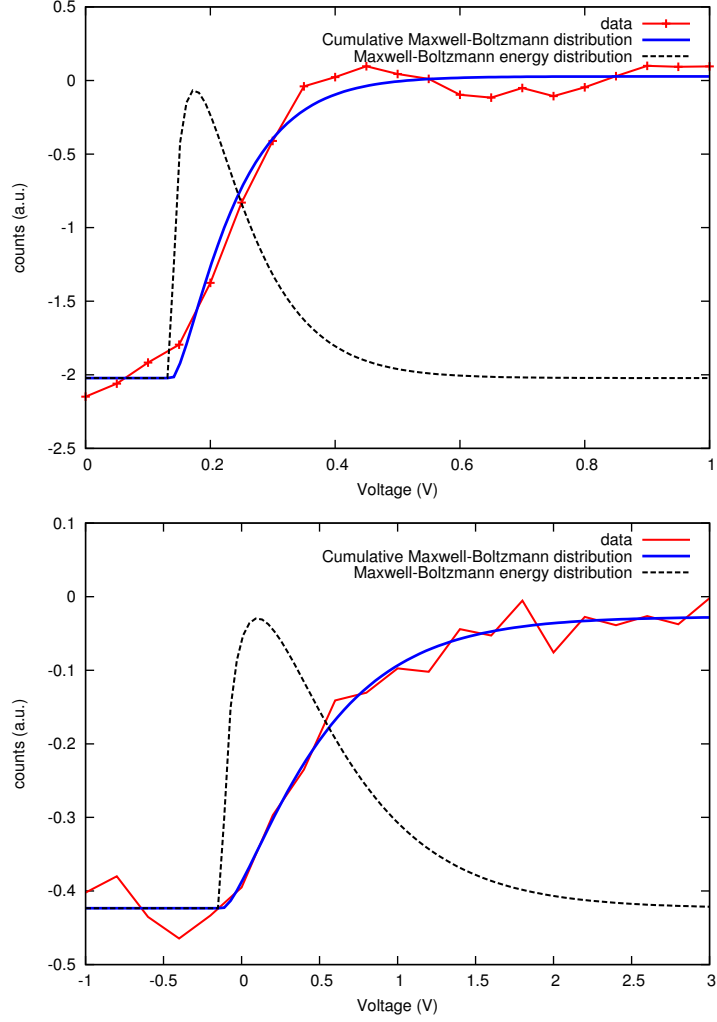


Figure 6.11 – Examples of measured energy distributions of the ion cloud. The ^{39}K ions were cooled for 1.8 s with a pressure of $\sim 7 \cdot 10^{-3}$ mbar in the buffer gas cross piece. The endcap voltage was 5 V. The **top** panel shows the energy distribution for ions in the cooler trap, where the distribution itself is measured over different measurement cycles and by changing the voltage on the main retardation electrode. The **bottom** panel shows the same, but for ions from the decay trap; i.e. they had already been transferred from the cooler trap. Both energy distributions are fitted with a Maxwell-Boltzmann energy distribution with two degrees of freedom, allowing for a shift in the retardation potential. The Maxwell-Boltzmann energy distribution is only shown for reference; the actual fit function is the cumulative distribution function. Good agreement with the experimental data is seen.

only the axial energy, whereas the retardation spectrometer will probe the total energy, which also includes converted radial energy. In figure 6.11 two examples of such an energy distribution are shown. The top panel is for ions in the cooler trap, while the bottom panel is for ions from the decay trap after the transfer. The mean energy of the Maxwell-Boltzmann distribution is 0.070(8) eV for the top panel, with a shift of 0.14(1) eV. In the bottom panel the mean energy is 0.44(6) eV with a shift of $-0.12(6)$ eV. Note that the first result is only three times higher than what can be obtained for an ion cloud in thermal equilibrium with a buffer gas at room temperature.

There are, however, also some issues with this method. To eject the ions from the traps, one or more electrodes have to be switched to a different voltage. Inherently this will alter the energy distribution of the ions. This will be reduced if the endcaps are lowered in small steps. The only way to measure the initial distribution directly is by doing an measurement on an isotope with an electron capture decay. Additionally, simulations can assist in deducing the correct energy distribution before switching the electrodes.

Change of phase space: Losses in the decay trap

Losses in the decay trap were first measured during the ^{124}In run of 2006 by looking at the half-life of the radioactive decay [Beck et al., 2011]. An upper limit of 2.6 % per second at a confidence level of 99.5 % was determined. An additional measurement to check for possible decay trap losses was performed in connection with the ^{35}Ar run in 2009. This was especially important as during the ^{35}Ar run of 2007 the losses due to charge exchange in the cooler trap had a ‘half-life’ of 8 ms. The losses were not checked with a radioactive beam, but with stable ^{36}Ar . This measurement was spread over several experimental cycles; each time the trapping time in the decay trap was prolonged. The results are shown in Fig. 6.12. There is quite some scatter in the data points due to fluctuations in the source. To verify that these variations are purely random, it was verified whether they follow a normal distribution. To this end the data points were projected onto the y axis into suitable bins. The resulting graph was fitted with a gaussian curve. A skew of the distribution would give an indication of a time evolution of the signal, but this was not the case. Within 5.5 s the signal is constant; fitting the data (of the top panel) with a linear function shows an increase of the signal, but consistency with zero losses within two standard deviations.

Longer measurements like this have to be done - e.g. 10 times longer measurement times - to magnify small losses that might be present in a measurement time of only a few seconds. Besides losses one can also look whether the radial distribution of the ion cloud in the decay trap changes over time. This has been investigated with data from the ^{124}In run, similar to the analysis explained in section 6.3.1. No change of the FWHM of the beam spot size on the detector can be seen; the ion cloud radial size in the decay trap thus does not change noticeably. From this rough analysis (i.e. see figure 6.10, top panel) the ion cloud radius was found to be 2.29(43) mm during the entire measurement.

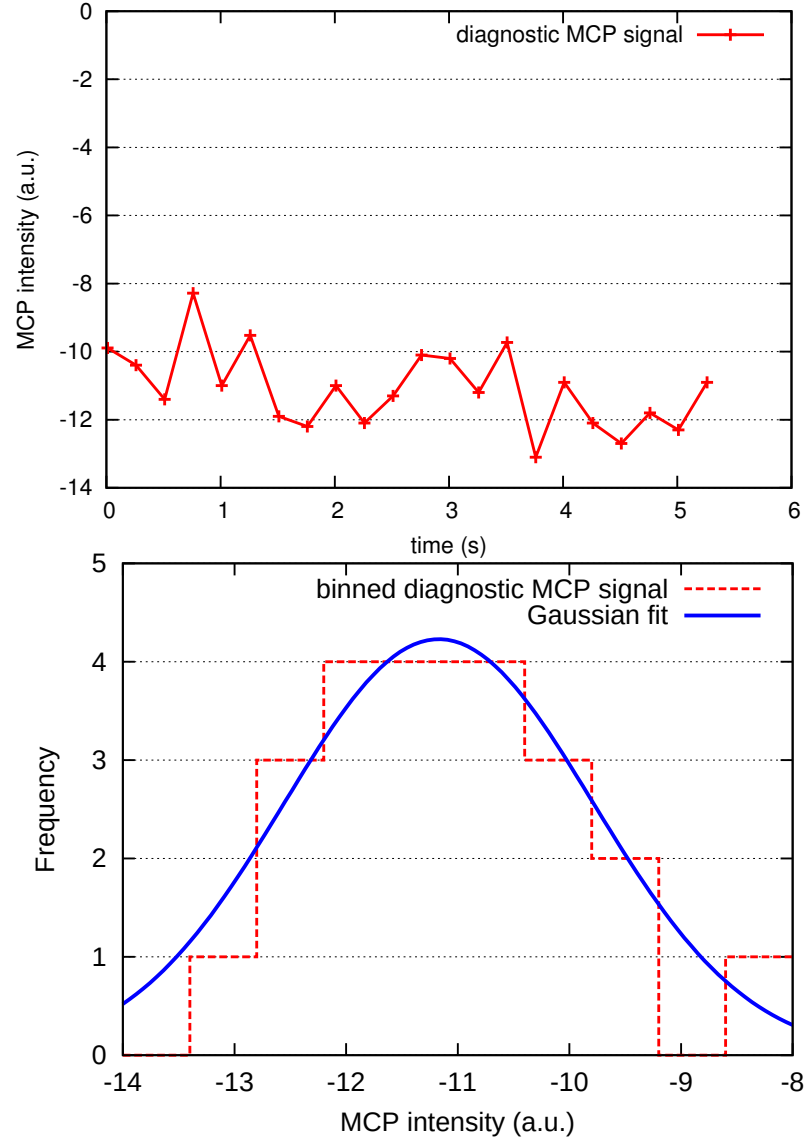


Figure 6.12 – The **top** panel shows the evolution of the MCP signal as a function of the trapping time in the decay trap. The **bottom** graph is a histogram of a projection of these points onto the y axis. The Gaussian fit has a mean of $\mu = -11.17$ and a standard deviation of $\sigma = 1.383$.

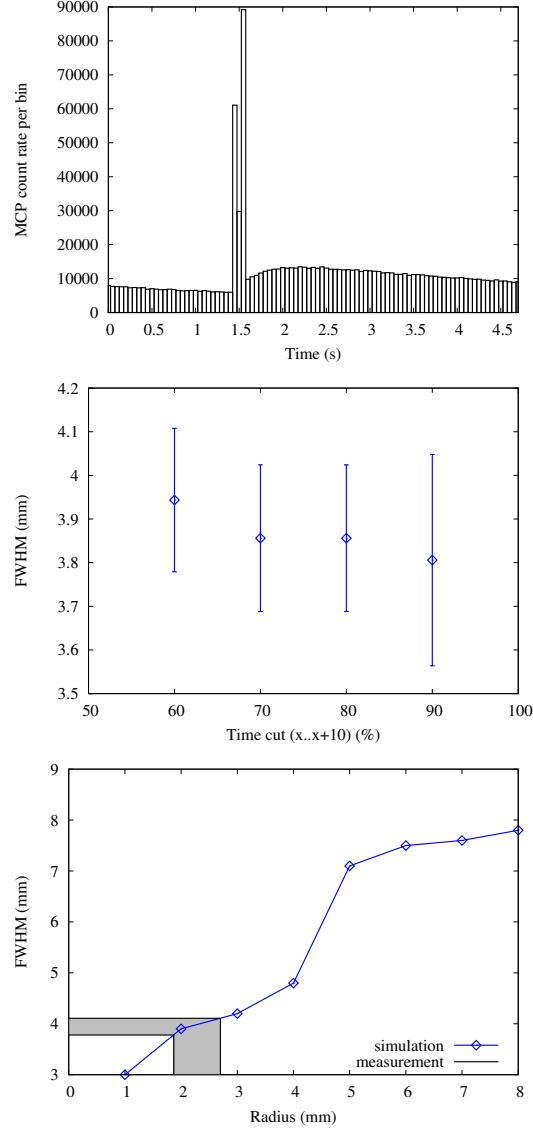


Figure 6.13 – In the **top** panel the full experimental cycle is shown. First the ions are prepared in the cooler trap after which they are transferred to the decay trap. The large peak are ions being shot over the decay trap onto the detector. During this the MCP goes into saturation and needs to recover for ~ 1 s. The position information was taken from $[2.65 : 3.1]$ s, $[3.1 : 3.6]$ s, $[3.6 : 4.1]$ s and $[4.1 : 4.7]$ s. The FWHM of the beam spot on the detector for these different time cuts is shown in the **middle** panel. All spot sizes from different time cuts are in agreement with each other; the radial distribution of the ion cloud does not change noticeably. In the **bottom** panel it is shown how the FWHM of the detector spot size corresponds to the ion cloud radial size in the decay trap.

6.3.2 Spectrometer

Measurements for the characterisation of systematic effects in the spectrometer are still in a very early stage. Simulations are ongoing, but still have to be checked against measurements. Here the effect of the applied potentials in the spectrometer is described, and a method is presented to accurately determine the magnetic field in the traps and spectrometer accurately.

Energy Filter: Applied Potential

The potential generated by applying the same voltage from a power supply on different metals is not necessarily the same. The contact potential difference (or Volta potential) is the potential difference that exists when two different metals are brought into contact with each other. For isolated metals the vacuum potential level can be anything. When they are brought into contact, charges will flow from one metal to the other until the Fermi levels are equal. As a results of this, the vacuum level will shift as well. The difference in vacuum levels, ΔV , is given by;

$$\Delta V = \Delta\varphi/e \quad , \quad (6.3)$$

where $\Delta\varphi$ denotes the difference in work function and e is the elementary charge. This is not an issue when the whole system is made out of the same material. However, at WITCH the source is located within gold-plated trap electrodes, while the electrodes of the retardation spectrometer are made of stainless steel (316L). The work function of gold is $\varphi_{Au} \approx 5.4\text{ eV}$ and that of stainless steel is $\varphi_{SS} \approx 4.4\text{ eV}$. Thus, an applied potential of 0 V is not the same in the traps and in the spectrometer. In addition, the exact work function of a material is heavily dependent on the exact chemical and crystallographic conditions of the surface. Orientation of the crystals and exact composition – in the case of steel – are very important. Also variations of the order of 10–100 mV are possible over a gold-coated surface; this is the so-called patch effect which has been investigated for the aSPECT and Nab experiments [McGovern, 2010].

To a first approximation this effect can be quantified with energy scans – of ions ejected from the cooler trap – carried out with the trap electrodes and the first three retardation electrodes. Also an electron capture peak measurement will provide this potential difference. But ultimately, when a more thorough control of systematic effects is required the surfaces of the electrodes will have to be characterised. The effect of an energy shift in the spectrum can be seen in figure 6.6.

Energy Filter:

Magnetic field determination via ω_c resonance

Exact knowledge about the ratio of the magnetic field strengths in the decay trap (i.e. the radioactive source container) and the analysis plane of the spectrometer (where the axial energy of the recoil ions is probed) is required to quantify the adiabatic conversion of radial energy into axial energy. Several methods can be

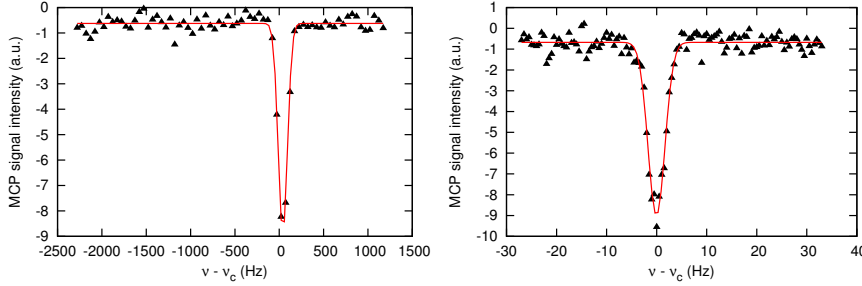


Figure 6.14 – Measurement of the cyclotron frequency for ^{133}Cs ions in the cooler trap. In black are the data points. The red lines are a fit assuming a Gaussian distribution. To the **left** a broad resonance frequency scan is shown. To the **right** a more narrow frequency scan is shown; the central frequency is $694316.96(5)$ Hz with a standard deviation of $2.38(5)$ Hz.

applied to measure a magnetic field, but Penning traps provide themselves a very accurate method to determine the magnetic field in the centre of the trap.

The cyclotron frequency of an ion in a Penning trap can be determined very precisely by applying a quadrupolar excitation. From a measurement of this frequency for an isotope with a precisely known mass, the magnetic field can be deduced with very high precision. The cyclotron frequency for a single ion is given by;

$$\nu_c = \frac{qB}{2\pi m}, \quad (6.4)$$

with q and m the charge and the mass of the excited particle respectively and B the magnetic field strength. The relative uncertainty on q is $\sim 2.5 \cdot 10^{-8}$ [Nakamura et al., 2010] and the relative uncertainty on m for ^{39}K and ^{133}Cs is $5 \cdot 10^{-9}$ and $1.7 \cdot 10^{-10}$ respectively [Wapstra, 2005].

A precise determination of the magnetic field thus requires a precise determination of this cyclotron frequency in the experiment. The cyclotron frequency can be determined both in the cooler and in the decay trap. First an example determination of the magnetic field will be given based on data taken in the past. Next an ‘ideal’ procedure will be outlined to extract as much data as possible on the magnetic field strength.

An example measurement of a cyclotron frequency determination is given in Fig. 6.14. First a scan over a broad frequency range is performed to get a good idea of the value of the cyclotron frequency. Afterwards one can switch to scanning a much reduced frequency region until the required precision is reached. The narrow resonance in Fig. 6.14 (right panel) was obtained with an excitation time of 1.3 s and an amplitude of 0.03 V. Two series of measurements¹ were done separated by 24 hours as shown in Fig. 6.15 on the left. The average of the first series is $6.0083357(3)$ T and the average of the second series is $6.0092268(8)$ T.

¹A series of measurements is in this case a period of a few hours where several frequency scans were done to test the traps.

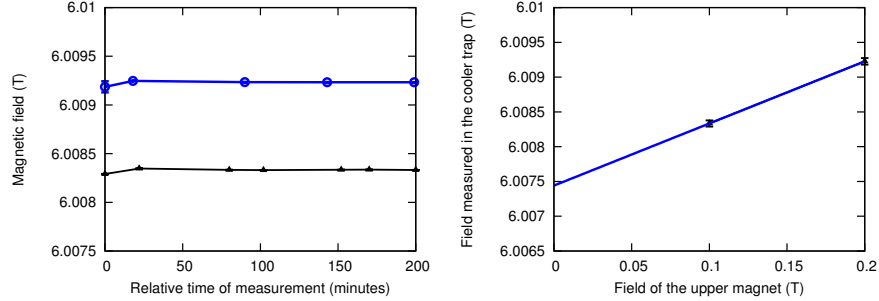


Figure 6.15 – Left: Results from two series of cyclotron frequency measurements for ^{133}Cs in the cooler trap for a magnetic field of 6 T in the lower magnet and of field of 0.1 T (black triangles) and 0.2 T (blue circles) in the upper magnet. **Right:** The averages of both data series are plotted as a function of the magnetic field from the upper magnet.

The uncertainties correspond to a relative uncertainty of the order of 10^{-7} . The difference between the two series is caused by the change of the magnetic field of the upper magnet from 0.1 T for the first series to 0.2 T for the second series. From these two data points one can determine the magnetic field in the cooler trap when the upper magnet is switched off (Fig. 6.15, right panel). Since there are only two parameters and two data points, this is a fully determined fit, and the value is 6.0074447(8) T.

The determination of the magnetic field strength can be taken even one step further. The measurements in the cooler and decay trap can also be used to obtain a precise value for the magnetic field in the analysis plane. According to the field map provided by Oxford Instruments (i.e. the constructors of the magnet) the magnetic field strength in the cooler and decay traps when the upper magnet is set to 0.2 T is 0.002182 T and 0.003496 T, respectively. In the given example the field strength in the cooler trap in the absence of the upper magnet was evaluated to be 6.0074447(8) T. If we subtract this from the measurements done at 0.1 T and 0.2 T we get a value for the stray magnetic fields of the upper magnet in the cooler trap of 0.0008910(9) T and 0.0017821(11) T respectively. This corresponds to a field of 0.081 T and 0.164 T according to the provided field map, instead of the supposed 0.1 T and 0.2 T values, respectively.

The deviation can be caused by;

- An inaccuracy in the magnet power supply causing the set value not to be the same as the actual value. This does not seem very likely however, as the deviation is rather large - i.e. 20 %. Such a deviation is not seen for the lower magnet.
- The magnetic field in the trap region is disturbed by ferromagnetic material inside the setup (i.e. beamline and retardation electrodes from stainless steel, and more recently: the buffer gas tube, the NEG foil around the trap structure, etc.). This could well be the case, since the disturbances have

a magnitude of only $4 \cdot 10^{-4}$ T.

- An ion cloud containing several particles will respond differently to a quadrupolar excitation; a frequency higher than the cyclotron frequency will be necessary to influence the ion cloud. In this case, however, the shift is in the wrong direction.
- A slight difference in the magnetic field created by the lower magnet between the two measurement series can have a large influence on this discussion. It is known that the current in a superconducting magnet slightly decreases over time [Kellerbauer et al., 2003] for instance. Also the precision of the power supply of the magnet can play a role in this, although, based on the field determination of 6.0074447(8) T before, the precision is of the order of 0.1 %. Both effects will influence the slope of figure 6.15 (right panel) and thus also a correct extraction for magnetic field value for the upper magnet.

With this method the field strength of the upper magnet can, in principle, be measured with a precision of 0.06–0.1 %, once the source of the discrepancy has been identified. This error is rather small already, but additionally one has to take into account that it is the ratio of two magnetic fields which is important for the conversion of radial into axial energy. With 6 T and 0.1 T in the two magnets, this ratio is $0.1/6 = 1.667\%$, meaning that the remaining radial energy of an ion in the analysis plane is 1.667(2) % of the initial radial energy. For an ion emitted at an angle of 45 % with respect to the magnetic axis and with a recoil energy of 500 eV, the initial radial energy will be 250 eV of which only 4.167(5) eV will remain in the analysis plane, with the rest having been converted to axial energy. As it is not the radial, but the axial energy that is measured, the axial energy of the initial event will be measured to be 495.833(5) eV. The error of 0.005 eV is a negligible systematic effect. Indeed, a deviation of 1 % in the magnetic field ratio is negligible for a correct determination of a (see figure 6.7).

This procedure should still be improved however. First of all a similar measurement should be done in the decay trap as this will hold the radioactive source for the experiment. Because of the absence of buffer gas and of a pumping diaphragm there, one could for instance use the time-of-flight method that is used for mass measurements. In principle this should yield the same precision for the magnetic field, if not better. Furthermore, this type of measurement should be performed in a more controlled fashion to avoid large uncertainties as was the case for this first measurement; e.g. perform these two measurements (with 0.05 T, 0.1 T and 0.2 T generated by the upper magnet) shortly after one another. A measurement with a magnetometer in the analysis plane will allow a calibration of the stray field of the upper magnet in the lower magnet; finding the source of the above-mentioned deviations is then not required any longer.

6.3.3 Detector Effects

Degradation of Detector

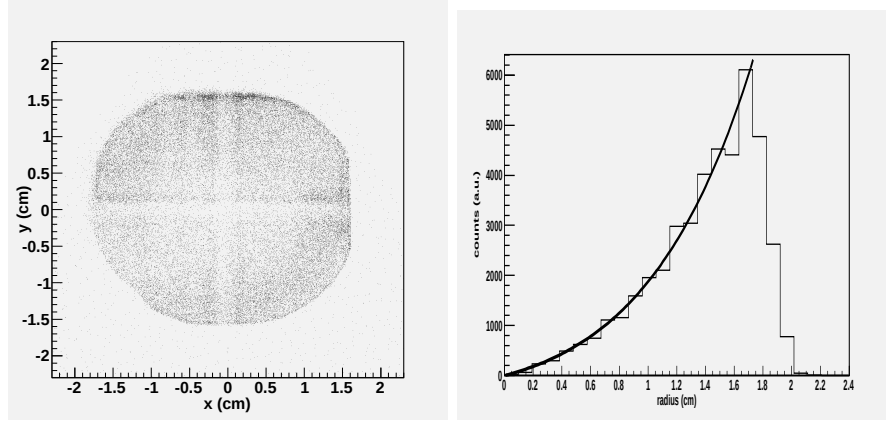


Figure 6.16 – Left: Intensity plot indicating the efficiency over the MCP detector surface. The ‘cross’ that can be seen on the left is an artefact from the data-acquisition electronics and not a decreased detection efficiency. On the **right** the radial distribution of the counts is shown. This function was fitted with ‘ $A \cdot r \cdot \exp(r/B)$ ’, yielding $A = 755.9(4)$ and $B = 1.1008(4)$. This type of distribution gave the best correspondence to the data.

A degradation of the detector was observed during the radioactive run of June 2010. The efficiency over the detection surface was measured with an ^{241}Am source placed at a few centimetres from the detector. The efficiency distributions are shown in figure 6.16. In the left panel, the position distribution of the counts is shown. Two features are present in this distribution; a ‘cross’ is present in the efficiency distribution and the efficiency in the centre of the detector is much reduced compared to the outer rim. The first effect is caused by the electronics and has been fixed in the meantime. The second effect is due to a degradation of the MCPs plates. Because more ions typically impinge on the centre of the detector, this area is the first to degrade. The efficiency in terms of the radius is shown in the right panel. It can be best approximated by a function of the form:

$$A \cdot r \cdot \exp(-r/B) \text{ for } r < 1.8 \quad . \quad (6.5)$$

Fitting the shown distribution gives $A = 755.9(4)$ and $B = 1.1008(4)$. Also the delay lines were later determined by the manufacturer to have an efficiency loss of about 25 % in the centre. In the meantime a new detector has been installed with a twice as large diameter, i.e. 8 cm instead of 4 cm.

In the future, a measurement of the efficiency over the entire detector surface will be performed before and after every radioactive run. Also, a distinction will have to be made between the efficiency of the MCP and the delay lines.

A reduced efficiency of the delay lines will not influence the measured recoil ion energy spectrum, but it might lead to some wrong conclusions during the investigation of systematic effects.

6.4 Summary and Conclusion

The influence of experimental conditions on a determination of a has been investigated; quantitative information about the systematic effects considered in this chapter are listed in table 6.1. Many systematic effects are identified at the moment and some more effects might be added to this list in the future. Some effects are well under control already and do not influence the determination of a ;

- The voltage applied to the endcap electrode of the decay trap is sufficiently precise, i.e. ~ 10 mV.
- The ratio between the low and the high magnetic field can be measured with a precision much higher than 1 %.
- The voltage applied to the retardation spectrometer is precise to 0.1 %.
- The energy distribution of the ion cloud can be determined within 10 %, which does not cause a deviation in a .
- A shift of the potential in the analysis plane has not been investigated yet, but this can be taken into account in the data-analysis as a free parameter.
- The half-life of ^{35}Ar has an uncertainty of 0.0010 s which is sufficiently precise for most types of measurement cycles.

Others have not been investigated yet and might have a large impact on the data-analysis. The important ones in this respect are the knowledge of the spatial distribution of the ion cloud, ion losses from the decay trap, a correct characterisation of the detection efficiency over the detector surface and a retardation-dependent background count rate.

The spatial distribution of the ions in the trap is important as this defines the source, which is the starting point for tracking simulations, and it determines the Coulomb potential that is generated by the ion cloud. This potential for a low number of ions, i.e. below 10^4 ions, is not significant. But for 10^6 ions or more, which is envisaged for the number of ions in the decay trap, this effect is significant. For a correct interpretation of the spectrum, the number of ions in the cloud should be known with an absolute precision of about $1 \cdot 10^5$ ions. To this end a new diagnostic detector should be installed in the spectrometer, for instance a Faraday cup with a pre-amplifier for detection of low ion numbers (10^5 ions which corresponds to 0.17 pA). The distribution of the ion cloud is important to correctly estimate the Coulomb potential generated by the cloud, and also the evolution of the spatial distribution during a measurement is important in this respect.

Table 6.1 – A summary of quantitative information of systematic effects during a measurement. The first column is a short description for the effect and it also lists effects which have a similar effect on a recoil ion energy spectrum. The next three columns tell how large the deviation from the assumptions during a measurement have to be in order to cause a certain shift of the value of a (S) or to cause a certain increase in the precision with which a can be determined (Δa). For instance, if the magnetic field ratio is off by 9 %, this will result in a wrong determination of a that is off by 1 %. Similarly, if the magnetic field ratio is off by 15 % this will increase the uncertainty of a to 0.5 %. Not applicable (N/A) means that there is no effect or that the effect has not been simulated for such large deviations. The latter is only the case for the precision of the magnetic field ratio. The last three columns indicate whether the effect has been investigated or can be quantified already, and if so, how large the effect at most is, and whether this is significant (under the current constraints).

Effect (units)	$S = 1\%$ $\Delta a = 1\%$	$S = 0.5\%$ $\Delta a = 0.5\%$	$S \leq 0.2\%$ $\Delta a \leq 0.2\%$	Inv.?	Est. magnitude	Sign.?
Ion losses (%/s)	0.2	0.1	0.05	✓	$\leq 2.5\%/s$	✓
Similar: Retardation-dependent ionisation, inhomogeneous detection efficiency						
Error half-life (s)	N/A	N/A	N/A	✓	0.001	
Shift Ret. Pot. (V)	0.01	0.005	0.002			
Similar: Retardation-dependent ionisation, inhomogeneous detection efficiency						
Ret. Pot. imprecision (V)	0.35	0.2	0.1			
Similar: Contact potential, Recoil ion cyclotron phase spectrometer						
Wrong E distr. (K)	N/A	N/A	N/A	✓	0.1 %	
(5 V bins)						
Wrong E distr. (K)	5000	2000	800	✓	10 % deviation	
(ass.: 293 K)						
Similar: Ion cloud axial size						
Prec. Magn. field ratio (%)	9	4.5	2	✓	$\ll 1\%$	
(5 V bins)						
Error on endcap voltage (V)	N/A	15	4			
(ass.: 1 V)						
Ion cloud potential (ions)	2	1.4	1.1	✓	1.01 V	
Similar: Recoil ions' start potential, changing Coulomb potential because of radioactive decay						
	$\pm 6 \cdot 10^5$	$\pm 3 \cdot 10^5$	$\pm 1 \cdot 10^5$			✓
	$\pm 4 \cdot 10^6$	$\pm 2 \cdot 10^6$	$\pm 5 \cdot 10^5$			

The energy distribution of the ion cloud is closely related to its preparation. While the determination of a is not as sensitive to a wrongly assumed energy distribution as was previously thought [Coeck, 2007], this is still an important effect. In this text it was assumed that the ion cloud will obey a Maxwell–Boltzmann energy distribution when in thermal equilibrium with the buffer gas, which is a valid assumption (see figure 6.11), however, a shift in energy due to the transfer still has to be taken into account.

Ion losses from the decay or an adopted value for the half-life that is not accurate enough, are important time-dependent effects. For ^{35}Ar the latter is not an issue. These time-dependent effects can have a big influence on the recoil ion energy spectrum. If the entire voltage range for the retardation spectrometer is scanned during one experimental cycle, small trap losses (0.1 %/s) can alter the shape of the measured recoil ion energy spectrum significantly (shifting a with 0.5 %). There are two possibilities to tackle this effect. Potential ion losses from the decay trap should be quantified before an experiment and they have to be determined very precisely. However, all measurements until now are consistent with no losses from the decay trap. Especially if the pressure in the decay trap is lowered – e.g. by the installation of a pulsed buffer gas system – there is no reason why there should be ions escaping the trap, besides the recoil ions of course. Another approach for this systematic effect is to alter the experimental cycle and keep the retardation voltage constant during a measurement. In this way potential ion losses from the decay trap will be the same for every retardation voltage. This requires the use of a normalisation detector so as to correctly interpret the spectrum.

The efficiency over the surface of the detector is important as well. In principle, if the efficiency fluctuates randomly this will not influence the spectrum too much. However, if these fluctuations are regular – as e.g. a reduced efficiency in the centre –, this will have an influence on the shape of the recoil ion energy spectrum. As the focussing of the recoil ions depends on their initial energy, fluctuations in the detection efficiency will induce energy-dependent effects. Therefore it is foreseen to characterise the detector before and after every important measurement.

The retardation-dependent ionisation effect is the most harmful and can prevent even the acquisition of a good recoil ion energy spectrum. It has been discussed extensively in chapter 5. Offline tests with a β^+ source or a (relatively) stronger γ source are essential to get this effect under control. Additional measures can be taken to reduce the effect. The electrodes upstream of SPACCE02 should be treated to reduce the electron yield from the electrode surfaces. This can be done with a NEG coating for instance. The ionisation of rest gas atoms can be further reduced by lowering the rest gas pressure; since this consists mainly of helium atoms during a measurement the partial pressure of helium should be reduced. This can be realised by the installation of a pulsed buffer gas system. Helium would then only be inserted in the cooler trap when the ion cloud is being prepared. After the preparation of the ion cloud the helium gas will be quickly pumped away.

Chapter 7

Perspectives

In this chapter the current status of the experiment, which forms the basis for possible upgrades and investigations in the future, is briefly reviewed. The technical improvements that are mentioned below are not required for a first determination of the β - ν angular correlation coefficient, but they can make this more efficient and can reduce known systematic effects. Most of the investigations mentioned below are necessary requirements for a precise determination of a ($\delta a < 1\%$). Finally other physics possibilities are briefly discussed as well.

7.1 Current Status

After the upgrade campaign the experiment was ready for a first measurement of a recoil ion energy spectrum on ^{35}Ar in 2009. This was nearly accomplished, but was then hampered by the remaining small secondary ionisation effect. This issue has been studied since and is also under control in the meantime so that a recoil ion energy spectrum from the decay of ^{35}Ar can be measured during the next radioactive run. When this is realised, the study of systematic effects should be intensified so that a first value for a can be extracted.

7.2 Investigation of Systematic Effects

At first the topics mentioned in this section will be investigated, but in the long term all the issues of chapter 6 will have to be addressed while also new effects might be identified and then have to be quantified along the way.

7.2.1 Trap Tests

Important for data-analysis are the properties of the ion cloud. Detailed investigations of trap properties will have to be performed in the near future. The first

step is to optimise the traps; the focus will mostly lie on lowering the energy of the ion cloud and being able to reproduce low energy distributions in different circumstances (e.g. different ion number, different ion species). Optimising the transfer from the cooler trap to the decay trap is crucial in this respect. During the initial tests also some new things will be tried like a quadrupolar excitation in the decay trap or replacing the helium buffer gas with neon buffer gas to try improving the cooling process – in terms of reducing the cooling time while keeping the same trapping efficiency.

In a second phase, the properties of the ion cloud in the decay trap will have to be studied more closely. This mainly relates to the effects listed in chapter 6 like the spatial and energy distribution of the ion cloud and how this might evolve over time. These measurements, in combination with simulations, will yield a complete picture of the properties of an ion cloud with 10^4 – 10^6 particles in a Penning trap. These results are also interesting for other experiments.

7.2.2 β^+ Source

The issue of the retardation-dependent background at WITCH is under control at the moment. However, it would still be necessary to do measurements with a β^+ source in the system, in order to characterise the ionisation in more detail. For a precise determination of a ($\delta a < 0.5\%$) the background of the measured spectra has to be completely flat and well under control. The only events that may generate a signal that is not constant in time are the recoil ions and the β 's stemming from the decay. An alternative to a β^+ source might be a γ source in the re-acceleration section of the system; first it has to be shown though, that this is a valid alternative.

7.2.3 Transmission Function

Ideally the transmission function of the system should be measured with an electron capture decaying nucleus. However, as this will likely not be possible in the near future, one has to look for offline alternatives. One possibility is to excite the ions in the trap by a quadrupolar ω_c excitation. This will increase the radial kinetic energy of the ions. If the energy is measured both in the traps and in the spectrometer, the adiabatic conversion of the radial ion motion can be directly observed and characterised. Alternatively, doing an axial excitation in the traps can also be a way to give the ions a specific energy. Dedicated measurements of the transmission function can also be done by placing an ion source that can create more or less mono-energetic ions in the decay trap.

7.2.4 Characterisation of Detector

At the moment the detector is the subject of a thorough investigation. A full understanding has to be gained of how the detector behaves in different circumstances. Most important in this respect is the characterisation of the detector

efficiency over its entire surface. With the experience that is currently being acquired, a procedure will be developed which can be performed on a regular basis; before and after a radioactive run.

7.3 Technical Improvements

Although many improvements have already been implemented in the WITCH setup since the first ^{124}In run in 2006, there will always be room for further improvement and optimisation in such a complex apparatus. Some ideas for technical improvements are therefore presented in this section. The aim of these improvements is to further consolidate the current operation of the system and to reduce systematic effects.

7.3.1 Permanent Solution for the Secondary Ionisation

The wire in the main retardation electrode has solved the problem of the retardation-dependent ionisation. The implemented solution, however, is far from ideal as it disturbs the recoil ions on their path through the spectrometer. Absorption of ions leads to only a small loss of efficiency, but scattering effects could disturb the recoil ion energy spectrum. To minimise these effects several technical improvement could be made;

- An obvious solution to reduce the impact of the wire on the recoil ions, is to install a thinner wire. The wire should still absorb electrons in the spectrometer, so there is a lower limit for the thickness of this wire.
- To avoid inhomogeneities in the electric potential of the analysis plane a conductive grid could be installed in the spectrometer. At present the axial symmetry of the electric potentials around the magnetic field axis is broken by the conductive wire. Installing a conductive grid in the analysis plane would nearly restore the axial symmetry of the electric potentials, but would also cause more scattering and absorption.
- Installing a moveable wire would allow further characterisation of the ionisation; e.g. by measuring how long it takes for the ionisation to build up. Additionally, when the wire is moved away from the centre, it will minimise the effect on the recoil ion energy spectrum. It has to be tested whether this last option is feasible. The sweeping rate of the wire – i.e. the frequency of placing the wire in the centre and removing it again – should be high enough to avoid any build-up of electrons. However, during the measurement of a recoil energy spectrum, a wire moving through the spectrometer has to be avoided since this will modify the retardation potential in the analysis plane during the measurement.

The build-up of electrons could further be reduced by applying certain coatings onto the electrode surface, but at the moment it is not sure which material would be best. Furthermore, this will require elaborate tests.

7.3.2 Pulsed Buffer Gas

During a measurement, buffer gas flows continuously into the cooler trap and is removed from it by the pumps. However, having buffer gas in the cooler trap is only required for a limited period of the experimental cycle; i.e. when the ion cloud needs to be prepared for the measurement which is about 0.5–1 s out of several seconds. The installation of a pulsed buffer gas system – to only allow buffer gas in the cooler trap when necessary – will have several benefits;

- The rest gas pressure in the decay trap will be reduced during the measurement of a recoil ion energy spectrum which will lower the probability of recoil ions scattering on rest gas atoms.
- The rest gas pressure in the whole system will be reduced which lowers the probability of ionisation effects. This is useful for the operation of the traps – where ionisation can be created when switching the endcap electrodes to a different voltage –, but also for the operation of the retardation spectrometer – where potential sources of ionisation could be avoided.
- The cooling time of the ions in the cooler trap might be reduced by using shorter buffer gas pulses at higher pressures (which is now difficult due to discharges, see section 5.2.4), thus reducing the preparation time for the measurement.

At ClusterTrap [Schweikhard et al., 2003] such a pulsed buffer gas system is already in use [Habs, 1993]. The pulsing of the buffer gas is realised by means of a piezo valve; a piezo element can expand or shrink under the influence of an applied potential. Such a valve allows for short pulses (minimum $10\mu\text{s}$) at a high repetition rate (maximum 3.6 kHz). At WITCH pulses with a length of the order of 100 ms at a rate of 1 Hz are sufficient. The main advantage of a piezo valve is that no mechanical moving parts are required, ensuring a longer lifetime of the device.

7.3.3 Cryogenic Traps

Simulations have shown that WITCH can already be operated close to what is technically feasible. E.g. trap endcap voltages lower than 0.5 V would invariably lead to efficiency losses [Van Gorp, 2011].

Cryogenic trap electrodes – Penning trap electrodes at a temperature of 4 K for instance – are required to cool the ion cloud even further. In principle only the cooler trap needs to be cooled, or even the buffer gas in this trap. But this is technically not feasible as the temperature of the buffer gas increases quickly – i.e. of the order of milliseconds or faster – to the equilibrium temperature, which is the temperature of the cooler trap electrodes. At 4 K the most probable energy is $\sim 0.2\text{ meV}$ so that all ions could be trapped with endcap voltages of 3–5 mV. The main benefit from having cooled traps would be a better control of one of the major systematic effects – thermal Doppler broadening. But it should

be clear that implementing cryogenic traps constitutes a major upgrade of the system; not only will modifications be required to keep the trap structure at low temperatures – i.e. installation of a heat pump and a different trap structure with low heat dissipation and which constitutes of materials that can be operated at cryogenic temperatures –, but also the electronics will have to be stable at a very good level – i.e. much lower than the mean energy of 0.2 meV of the ions – to avoid disturbances of the ion cloud due to ripples in the potentials.

Several experiments already make use of cryogenic traps. In mass measurements this is required to use non-destructive measurement techniques like FT-ICR (Fourier Transform Ion Cyclotron Resonance) [Weber et al., 2005]. In antimatter experiments, the antiprotons are also first trapped in a Penning trap. Lowering their energy – which can be required for efficient antihydrogen production in certain experiments – requires the trap environment to be cold as well [Doser et al., 2010].

7.3.4 Normalisation β Detector

The normalisation β detector could not yet be tested during an online run. It is important to see whether the transmission through the beamline can be realised without a loss in efficiency; the use of the PIN diode array requires transporting the beam through an electrode with 8 mm diameter versus ~ 6 cm for the other beamline electrodes in the VBL. Secondly the β 's from an actual radioactive ion cloud have to be observed as it is not guaranteed that it will have a radius of 1–2 mm. The latter can still be tweaked if necessary, e.g. with the installation of a magnet to better focus the β 's, which is also beneficial for the beam tune as the ions will then be injected into the magnetic field at a higher kinetic energy.

7.3.5 Beamline Alignment and Transport Efficiency

The alignment of the vertical beamline is an issue that has been raised some time ago already (e.g. see [Coeck, 2007]). The electrodes in the horizontal beamline have been aligned upon installation, but for the vertical beamline this was not yet done. The main problem with this is that the vertical beamline is ‘squeezed’ between the cryostat and the horizontal beamline – thus not allowing open access from one of the two sides – and the fact that it is slid out from time to time to access the Penning trap structure. However, the injection of the ions into the magnetic field is the cause of the main remaining efficiency loss in the beam transport. To optimise this, a parallel beam – and thus a well-aligned beamline – is required.

It has to be noted here that with the recent technical upgrades the alignment of the vertical beamline has become somewhat less critical. Indeed, due to the higher repetition rate of the pulsed drift tube, the amount of accumulated ions in the traps can now be more easily increased. If REXTRAP emits an ion bunch containing 10^6 ions and using a realistic value of 20 % for efficiency for the beamline transport, a repetition rate of 5 Hz will yield an ion bunch that

is already close to the space charge limit of the cooler trap. Of course, this argument is not valid anymore when the space charge limit of the traps cannot be reached.

7.3.6 Recoil Detector

The use of a solid state detector to observe the recoil ions has been discussed in the past already (e.g. see [Coeck, 2007]). The advantages are obvious; not only will it allow for a precise determination of the recoil ion energy, but β 's and different charge states can in principle easily be distinguished as well. The latter is possible due to a different acceleration of the ions towards the detector. This would greatly improve and enhance the analysis of data. However, a solid state detector requires a depletion layer which is created by a contact layer on the front and back sides of the active area. Ions need to be able to cross the front contact layer to produce a (very low) signal in the detector. Reducing the contact layer so that ions can more easily pass has reached its technical limits; the smallest contact layers (i.e. of about 25 nm) are exactly created by ion implantation.

An overview on the fundamental limits of silicon solid state detectors is given in Ref. [Funsten et al., 2004]. However, improvements of existing technologies [Lepri et al., 2006] or new technologies altogether [Shiki et al., 2009] suggest that the detection of low-energy ions might be practical in a few years from now. Important constraints from WITCH that are currently preventing the use of these new developments are the large detection surface that is required (i.e. at least about 6 cm diameter), fast response to single ions and – optionally – position determination of events.

7.4 Physics Opportunities

Many physics goals besides the measurement of scalar currents in the weak interactions have been proposed in the past [Delauré, 2004, Kozlov, 2005, Coeck, 2007]. Since a large range of isotopes is available at ISOLDE, other physics goals can be looked for across a large area of the nuclear chart. Some of the already mentioned opportunities are;

- Tensor interactions could be studied easily by measuring the β - ν correlation in a pure Gamow-Teller decay. ^{58}Mn has already been suggested in this respect [Coeck, 2007].
- The Fermi/Gamow-Teller mixing ratio can be deduced from the value of a , if one assumes no physics beyond the Standard Model.
- Q-values can be measured by determining the position of the electron capture peak in the recoil ion energy spectrum. This requires a very precise energy calibration though and cannot compete with precision Penning trap-based mass spectrometers, such as e.g. ISOLTRAP.

- The branching ratio of EC to β^+ decay can be measured.
- Different kinds of trap-assisted spectroscopy are possible. Including extra detectors around the trap region would allow to perform both β and γ spectroscopy. Moreover, this trap-assisted decay spectroscopy would allow to work with pure sources. This is currently under development at ISOLTRAP [Kowalska et al., 2009].

7.4.1 β Spectrum Shape

Measuring the exact shape of the β spectrum yields information about recoil order corrections in the weak interaction (see section 6.1.4). A compact β spectrometer is currently being developed in the group [De Leebeek, 2011]. This spectrometer consists of a multi-wire drift chamber combined with an energy-sensitive detector. The drift chamber will allow the exclusion of events scattered from this detector, thus allowing to construct a scattering-free β spectrum. In a first phase this spectrometer will be used with an offline source, e.g. ^{60}Co . Later on, to improve the determination of the spectrum shape, also a scattering-free radioactive source might be necessary. This could be provided by the WITCH setup.

7.4.2 Measurements on Other Nuclei

Apart from ^{35}Ar other isotopes are also good candidates to search for scalar currents in the weak interaction such as $^{26\text{m}}\text{Al}$ and ^{46}V (see Tab. 2.3). The first one is already available at ISOLDE, but the yield is still too low. A superallowed $0^+ \rightarrow 0^+$ transition (as $^{26\text{m}}\text{Al}$ and ^{46}V are) would be preferred, but other mirror nuclei can also be considered. Target development at ISOLDE might open up new possibilities for the isotopes to be measured at WITCH. For good candidates, see table 2.3.

7.4.3 Electron Capture Decay

A measurement of mono-energetic recoil ions coming from an electron capture decay would be a valuable test for the system. As has been mentioned before it would provide a precise energy calibration for the retardation spectrometer, while the measurement of the transmission function would be a good test for the particle tracking simulations. Additionally, new physics can be investigated if a electron capture peak is measured precisely. For instance, the admixture of a heavy neutral neutrino with the electron neutrino would create a second reduced electron capture peak at a slightly different energy. A feasibility study has been performed already [Coeck, 2007]; the required statistics can be obtained in one day. So even though the purity of the beam was not as expected during the run of July 2010, it is still worthwhile to put effort in the production of pure rare-earth beams.

7.4.4 Half-life of Highly Charged Two-Body Decay

Recently non-exponential electron capture decay of hydrogen-like heavy ions has been observed at the GSI in an ion storage ring [Litvinov et al., 2008]. This unexpected result stirred quite some interest in the nuclear physics community and beyond. Quickly theories were proposed to explain the observed oscillations; one of the first models invoked neutrino oscillations to explain the oscillations in the decay curves, whereas others suppose it is merely an artifact from the measurement method. The investigation of this effect is still ongoing at GSI [Winckler et al., 2009].

Confirmation was sought from other experimental methods. One of the good candidates to perform such a measurement is WITCH as it is closely situated to the charge breeder REXEBIS. However, several issues need to be solved to allow for such a measurement;

- REXEBIS needs to be able to produce highly-charged ions, but specifically hydrogen-like atoms. REXEBIS was designed to obtain charge to mass ratios in the range of 2.5–4.
- An extra beamline would need to be constructed between REXEBIS and WITCH. It is not possible to transfer the highly charged ions back to REXTRAP and then to WITCH as they would immediately charge exchange in REXTRAP.
- The charge exchange might also pose problems in the WITCH cooler trap. However, one could look at other cooling methods like stochastic or evaporative cooling. Maybe cooling is even not necessary at all and one could observe the half-life by trapping the ions immediately in the decay trap; this, however, will depend on the recoil energy of the isotope under investigation.

Due to these technical issues the intended measurement is on hold, as the measurement of the β - ν angular correlation in ^{35}Ar decay has highest priority at the moment.

Conclusion

In this work the WITCH setup has been presented. The primary physics goal of the experiment is to investigate the existence of scalar currents in the weak interaction. This is realised by a measurement of the β - ν angular correlation in nuclear beta decay. A precise measurement of this correlation coefficient allows extracting information on the coupling constants for the different weak interaction types in nuclear β decay. To measure this correlation the spectrum shape of the recoil ions after β decay will be measured very precisely. A precision on the β - ν angular correlation coefficient, a , of 0.5 % is the final aim.

First the experimental setup was presented. The radioactive ions necessary to measure the recoil ion energy spectrum are produced at the ISOLDE facility at CERN. The WITCH setup combines two Penning traps with a retardation spectrometer. A Penning trap is used as source to avoid scattering and energy loss of the recoil ions. The energy of the recoil ions is then probed by applying a potential barrier in the retardation spectrometer. By changing this potential barrier an integral energy spectrum can be obtained. Finally, the ions that pass the retardation barrier can be detected. At the moment the best isotope for the measurement, taking into account technical and physics constraints, is ^{35}Ar .

To allow a measurement on ^{35}Ar upgrades to the setup were necessary. Major issues that were hampering a correct measurement of a recoil ion energy spectrum from ^{35}Ar decay were the neutralisation of ^{35}Ar in the cooler trap and ionisation effects in the spectrum. The first prevented a proper preparation of the ion cloud before transferring it to the decay trap, while the latter caused large fluctuations in the count rate of the background. A major part of the upgrade was an improvement of the vacuum to avoid neutralisation and reduce the ionisation effect. In most of the volume the rest gas pressure was reduced with one order of magnitude (from $5 \cdot 10^{-8}$ mbar to $5 \cdot 10^{-9}$ mbar) and in the pulsed drift tube section even with two orders of magnitude (from $5 \cdot 10^{-8}$ mbar to $5 \cdot 10^{-10}$ mbar). Another major part of the upgrades was the installation of a shield around the REX-ISOLDE mass separator and the construction of a small RFQ to obtain bunched beams from the surface ionisation source. These two upgrades were necessary to increase the testing time available for WITCH, which was in the past limited to a few weeks every year; most often during the preparation for a beam time. Other upgrades were also done to increase the flexibility of the system and to allow for different measurement cycles.

The ionisation effect was unfortunately not yet completely removed during the last ^{35}Ar run. This prompted a detailed investigation of this effect based on experimental data – taken during radioactive runs and dedicated offline tests – and simulations. The ionisation effect is caused by Penning-like electron traps in the spectrometer. These trapped electrons can in turn ionise rest gas atoms (i.e. helium during a measurement) which can be accelerated towards the detector. Since the amount of ions created depends on the applied retardation voltage, an increased background count rate was observed during higher retardation voltages, which is the most disturbing effect during the measurement of a recoil ion energy spectrum. The loading of this electron trap is now prevented by the installation of a conductive wire through the analysis plane which absorbs any electron that gets trapped in the spectrometer.

Finally, to reach the goal of WITCH – measuring a with a precision of 0.5% – a good control of systematic effects is vital. Systematics effects that have been investigated already, as well as effects that have recently been identified are discussed again and their effect on a is quantified where possible. The most important sources of systematic effects that need to be studied in detail in the near future are the properties of the ion cloud and the characterisation of the detector. The spatial distribution of the ion cloud needs to be known to good precision as this is the starting position of the recoil ions. The characterisation of the detector is important to avoid energy-dependent effects.

The setup is now ready for a good-quality recoil ion energy spectrum from ^{35}Ar decay. The ionisation effect has been solved and important systematic effects have been identified. During a radioactive run it will be important to do as many measurements – next to the measurement of a recoil ion energy spectrum – as possible to quantify the systematic effects that have to be taken into account during analysis. After a first measurement of a recoil ion energy spectrum, undoubtedly other focus points will be identified. In combination with a continuation of the study of systematic effects this should lead to a good determination of a ($\delta a \approx 1\%$) before the CERN shutdown period in 2013.

Appendix A

Control System

In this appendix the article entitled *Computer Controls for the WITCH Experiment* is presented as published [Tandecki et al., 2011]. The full reference is:

- **Computer Controls for the WITCH Experiment**

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It describes the control system – i.e. the collection of computer controls – that was designed for the WITCH experiment. It is based on the LabVIEW *CS*-framework developed and maintained by the EE/KS (Experiment Electronics-/Control Systems) group at GSI. In section A.7 new additions and details not described in the article are presented.

Computer Controls for the WITCH Experiment

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A.1 Abstract

The WITCH experiment is a medium-scale experimental set-up located at ISOLDE/CERN. It combines a double Penning trap system with a retardation spectrometer for energy measurements of recoil ions from β decay. For a correct operation of such a set-up a whole range of different devices is required. Along with the installation and optimization of the set-up a computer control system was developed to control these devices. The *CS-Framework* that is developed and maintained at GSI, was chosen as a basis for this control system as it is perfectly suited to handle the distributed nature of a control system. We report here on the required hardware for WITCH, along with the basis of this *CS-Framework* and the add-ons that were implemented for WITCH.

A.2 Introduction

The WITCH experiment (**W**eam **I**nteraction **T**rap for **C**harged **P**articles [Beck et al., 2003, Kozlov et al., 2008]) combines a double Penning trap system with a MAC-E filter [Picard et al., 1992], and is located in the ISOLDE facility at CERN [Kugler, 2000]. The primary goal is to use nuclear β decay to search for exotic admixtures (e.g., scalar currents) to the vector minus axial vector ($\mathbf{V} - \mathbf{A}$) structure of the weak interaction allowed in the Standard Electroweak Model. Currently the most general upper limit for a possible scalar interaction is

[Severijns et al., 2006]:

$$\frac{C_S}{C_V} < 7\%, \quad (\text{A.1})$$

with C_S and C_V the coupling constants for scalar and vector interactions, respectively. Such scalar admixtures are searched for at WITCH by performing a β - ν angular correlation measurement, which is realized by measuring the recoil energy of daughter nuclei after β decay. The primary physics candidate, taking into account several experimental constraints, is the mirror nucleus ^{35}Ar .

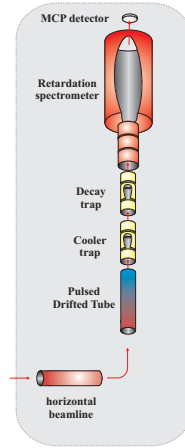


Figure A.1 – A schematic overview of the WITCH set-up at ISOLDE/CERN. Shown as encountered by the beam are the horizontal beamline (including the beamgate), the vertical beamline (including the pulsed drift tube), the cooler trap, the decay trap, the retardation spectrometer and a position sensitive micro-channel plate detector.

The lay-out of the WITCH set-up is shown schematically in Fig. A.1. Radioactive ion beams are produced at the ISOLDE facility which are bunched in the REXTRAP Penning trap [Ames et al., 2005]. The bunches from REXTRAP can be transported to the WITCH experiment. Typically the beam energy from ISOLDE is 30 keV for REX [Habs et al., 2000] operation. This kinetic energy needs to be decreased to tens of electronvolts, so that the ion bunches can be trapped in the WITCH Penning traps which are at ground potential. This change in kinetic energy is realized by the pulsed drift tube (PDT) switching over a range of 30 kV and a subsequent retardation. Afterwards the energy of the ions is low enough to allow trapping in the first of the two Penning traps; the cooler trap where helium buffer gas is present to cool and manipulate the ions. After the ion cloud is prepared in the first trap, it is transferred into the decay trap where it is kept for the measurement cycle.

The ion cloud in the decay trap acts as the scattering-free radioactive source for the WITCH experiment. Half of the recoiling ions from β decays in the decay trap are emitted into the direction of the retardation spectrometer. Since the

magnetic field is 9 T in the traps and is adiabatically lowered to 0.1 T in the spectrometer, the transversal energy of the recoil ions is converted into axial energy. The axial energy of the recoil ions is probed by applying a potential on the spectrometer electrodes. If the energy of the recoil ions is sufficiently high they can pass this barrier and be re-accelerated onto a Micro-Channel Plate detector (MCP). This is the working principle of a MAC-E filter. By scanning this retardation potential one can measure an integral energy spectrum.

To obtain this recoil ion energy spectrum many different systems need to work together; hardware, software and the communication between these components. Here we report on the hardware and software needed to be able to use WITCH as a tool for weak interaction studies. The data-acquisition method to measure a recoil ion energy spectrum is reported in Ref. [Kozlov et al., 2008].

A.3 The WITCH experiment

A.3.1 Requirements for the WITCH controls

To control and supervise the WITCH set-up between 300 and 400 parameters are to be set, monitored and saved. Here we will first give a general overview of the requirements of the control system as to e.g., precision, repeatability, stability, etc. In the following paragraphs more details will be given.

The transport of the ion bunch from REXTRAP to the WITCH cooler trap is realized by means of ~ 45 electrodes, the potentials for which are provided by several power supplies. Apart from setting and reading back voltages, additional control over the power supplies – like setting and reading back the ramp speed and reading out the current – is also desirable. Further, once a good beam tune is obtained the corresponding voltage settings need to be easily reproducible in future. This puts constraints on the technical specifications of the power supplies used such as the voltage stability over time and over a certain temperature range. Typically the voltage stability is in the range of $\Delta V/V_0 < 7 \cdot 10^{-4}$. Where very good stability is required, e.g., in the 90° bender, it is even better. The voltage stability over time is especially crucial as it reduces the time needed to set up the system for a measurement.

After the beam transport the ion bunch arrives in the cooler trap. The double Penning trap system consists – in its current form – out of 49 electrodes. The voltages applied on these are not static, but need to be changeable in a stepwise fashion to realize the different steps of the trapping cycle (see Fig. B.5). These changes are not triggered by software as this cannot provide the required accuracy, but have to be done by hardware devices. With the aim of obtaining a well-cooled ion cloud in the decay trap, these triggers need to be repeated with a precision of $0.1 \mu\text{s}$ and better. The full trapping cycle typically ranges from 100 ms to several seconds.

With the ions in the decay trap the experiment can be performed. The main technical difficulty here is the switching of the potential of the seven retardation

electrodes. This voltage needs to be applied and determined with good precision, as it will directly contribute to the systematic error of the recoil ion energy spectrum. The present requirements for the retardation power supply are a range up to 700 V, a switching time of $\sim 100 \mu\text{s}$ and a precision of 100 mV. For the five re-acceleration electrodes the same considerations as the beamline electrodes apply.

Finally, to operate the WITCH system a good vacuum is of course required. The vacuum system is not computer controlled as it is very critical and should not be subject to computer errors or failures. Even though it is not computer controlled, it is, however, monitored continuously via computers. With pressure gauges, pumps, controls for the valves and an interlock system, about 20–30 parameters need to be monitored on a regular basis; i.e., about every few minutes.

All these parameters need to be recorded when the data-acquisition starts. This is useful for future reference and for data-analysis.

A.3.2 Experimental cycle

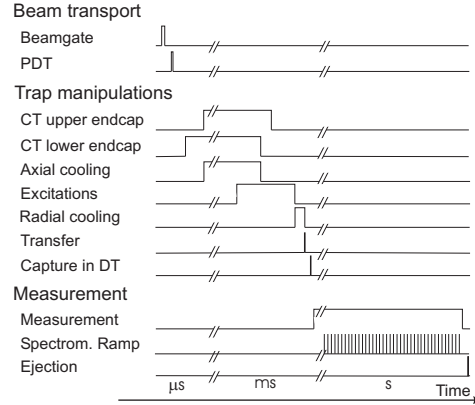


Figure A.2 – Schematic overview of the triggers used in a typical WITCH experimental cycle. CT and DT stand for cooler trap and decay trap respectively. PDT refers to the pulsed drift tube for lowering the relative potential of the ion bunch.

Many different steps are necessary to get the cooled cloud of radioactive ions in the decay trap to be able to probe their energy. A schematic overview of the full timing cycle for WITCH is given in Fig. A.2. First of all, the ion bunches have to be transported from REXTRAP to the first of the two Penning traps; the cooler trap. To this end around 45 electrodes have been installed in the horizontal and vertical beamline for guiding the beam. For most of these electrodes, a static voltage is applied, but for two electrodes the timing is of utmost importance.

The first of these acts as a beamgate; this is the first electrode in the horizontal beamline to which the voltage required for transmission is applied for only a few

microseconds in each cycle. This allows for a crude time-of-flight separation of unwanted ions, most notably ionized neon buffer gas coming from REXTRAP. The timing has to be adapted according to the mass of the ions of interest. The length of the beamgate is determined by the time of flight of the ion bunch in the pulsed drift tube; typically 2.5 to 4 μs .

The second electrode with varying voltage is the pulsed drift tube [Coeck et al., 2007a]. At this electrode the voltage is switched over a range of 30 kV in 1.5 μs while the ion bunch is traveling through it, in order to pulse down the potential energy of the ions from the value they have when leaving REXTRAP (i.e., 30 kV) to a value close to ground potential. This is necessary to enable their capture in the cooler trap. As with the beamgate the timing of this pulsing down is crucial.

When the ions are directed into the cooler trap the trapping cycle starts; a schematic overview of this is shown in Fig. B.5. Upon arrival in the cooler

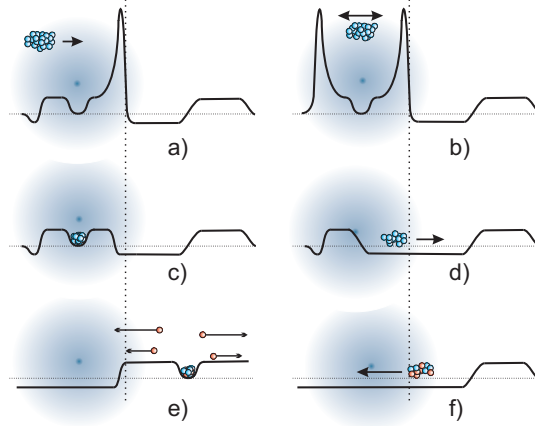


Figure A.3 – A typical trap cycle at WITCH. Each subpanel shows the cooler trap - with helium buffer gas - to the left of the dotted line and the decay trap to the right of this line. First (a) the cooler trap is opened to receive the ions. When the ion bunch is in the cooler trap (b) both endcaps are closed. The ions are cooled into the central quadrupole potential after which excitations can be applied (c) At this point the endcap potentials are lowered. Thereafter (d), the well-cooled ions are transferred from the cooler to the decay trap. There the ions are stored to allow detection of recoil ions (e). Finally (f) the ions that did not decay are ejected backwards.

trap the ions have an axial energy of tens of electronvolts which is decreased by collisions with helium buffer gas. The first step (Fig. B.5b) is to cool the ions from a box trap for capture to the bottom of the quadrupole potential which is the actual potential of a Penning trap (Fig. B.5c). With the ions in this quadrupole potential several manipulations on the ion cloud can be performed [Savard et al., 1991].

After the preparation of the ion cloud it can be transferred to the decay trap,

which is realized by changing the voltages in the cooler and decay traps (Fig. B.5d). The transfer potential is such that the ions from the cooler trap are sent into the decay trap without changing the properties of the ion cloud; i.e., the energy and position spread of the ions remain the same. This is realized by a Wiley–McLaren potential [Wiley & McLaren, 1955]. A low energy and a narrow energy distribution of the ion cloud is required to avoid a broadening of the recoil energy and thus assure a narrow response function. After this transfer the ions are kept in the decay trap for the measurement cycle (Fig. B.5e, [Kozlov et al., 2008]). As such the decay trap provides the scattering-free radioactive ion source for the experiment. At the end of a measurement cycle the ions that did not yet decay are ejected backwards through the cooler trap to avoid radioactive contamination of the detector (Fig. B.5f). Note that for diagnostic and tuning purposes, the ion cloud can be ejected upstream towards the spectrometer as well.

When the ions are stored in the decay trap the spectrometer acts as an energy selective barrier. The electric field of the spectrometer is generated by means of seven retardation electrodes which receive their voltage from a single power supply - the retardation power supply - and a voltage divider. The potential in the spectrometer increases from the trap to the analysis plane where it reaches the full retardation value. This gradual increase of the potential is necessary to ensure a good adiabatic conversion of the radial component of the ion's recoil energy into axial energy.

Typically the retardation voltage is ramped from 0 V to its maximum value during one measurement cycle in order to have a proper normalization. The starting and stepping of this power supply is synchronized to the capture in the decay trap and the data-acquisition. Recoil energy data are recorded as a function of time, but due to the synchronization a certain time corresponds to a certain applied retardation voltage in the spectrometer and thus a spectrum can be constructed.

A.3.3 Devices for the experiment

In this section the hardware devices are presented. They are divided into four categories; fast controls, slow voltage controls, data-acquisition and other slow controls. The properties of the experimental cycle along with the properties of the devices will set the requirements for the computer control system. An overview of the devices with some of their properties is given in Table A.1.

Fast controls

The fast controls include the devices necessary for the realization of the experimental cycle described in section A.3.2. Basically they consist of timing units, power supplies and frequency generators. A scheme of this is given in Fig. A.4.

The central part of the experiment is the timing unit. In the case of WITCH this

Table A.1 – Table with properties of computer controllable devices at WITCH. The manufacturer and model number are listed, as well as the communication protocol and the number of extra DIM services each CS object creates. A star (*) indicates the extra DIM services for only one channel of a device (e.g., on a multichannel power supply).

	device name/type	manufacturer and model no.	# DIM services	bus type
fast controls	GADU	IKS - 2003-49 03M29	20	RS232
	GADUv2	IKS - 2008-74 08M17	20	USB (RS232)
	EndcapSupply	IKS - 2006-29 06M19	4	USB (RS232)
	TrapSupply	IKS - 2008-70 08M15	32	USB (RS232)
	Freq. Generator	Stanford Research Instr. - DS345	13	GPIO
slow	Retardation PS	IKS - 2005-14 05M05	40	RS232
	steerer PS	IKS - 2002-58 02M20	10*	RS232
	bender PS	ISEG - NHQ234M	10*	CanBUS
	PS	ISEG - EHQ/EHS F020n	10*	CanBUS
	PS	ISEG - CPx	10*	CanBUS
	PDT(+) PS	FUG HCP 140-65000	1	analog
	HBEINZ PS	Spellman - RHSR30P060/220	1	analog
	Oscilloscope	TekTronix - TDS2024	1	GPIO
	Electrometer	Keithley - 6514	1	GPIO
	MCS	Ortec - MCS-PCI	-	PCI
other slow controls	Gauge read-out	Pfeiffer - TPG300	4*	RS232
	Gauge read-out	Pfeiffer - TPG262	2*	RS232
	Turbo pump	Alcatel - ATP450 & ATP900	-	RS232
	Valve control	IKS - 2002-59 02M21	32	RS232
	Magnet PS	Oxford Instr. - IPS120-10	-	GPIO
	Level meter	Oxford Instr. - ILM211	2	RS232
	Cryostat resistors	IKS - 2003-59 03M21	8	RS232
	Thermocouples	Picosystems - TC-08	9	USB

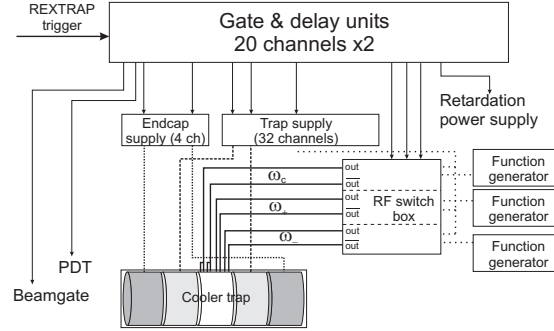


Figure A.4 – Electronics scheme of the fast controls for the example of the cooler trap.

is a **Gate & Delay Unit** (GADU). This unit basically consists of 20 channels with one input and two outputs based on TTL signals. The input triggers and output signals for these two units are represented in figure A.5. The first GADU uses an internal clock with a resolution of 100 ns and a jitter of 20 ns. It can also use an external clock; to this end another input is provided. The internal clock has a control of 32 bit thus allowing time windows or time differences ranging from 100 ns to about 430 s. The second unit (GADUv2) has a slightly better clock with a resolution and jitter of 20 ns. With this, time periods or differences ranging from 20 ns to 89 s can be set. With these two units the entire cycle of WITCH (Fig. A.2) can be controlled.

The devices required to operate the traps are also counted among the fast controls. These are power supplies, frequency generators and a device to combine both. There are two types of power supplies for the WITCH Penning traps.

First there is a need to trap the incoming ions that still have a relatively high energy (≤ 100 eV); for this purpose a so-called **endcap supply** was designed at the IKS, K.U.Leuven. This has four channels (to supply two endcaps in both the cooler and decay traps) which can be switched between two different levels. The low voltage level - which is active when the TTL signal is low - provides a voltage between -20 V and 0 V. The high voltage level - which is active when the TTL signal is high - can be set between 0 V and 450 V, as required to trap ions which have not been cooled yet. The switch between these levels occurs with a typical rise time of the order of a few hundred nanoseconds.

The second power supply, the **trap supply**, has also been developed in house in order to suit our specific needs. Each of the 32 channels of this power supply can provide a voltage between -15 V and 15 V. On top of that it is possible for each channel to sequentially switch between four different levels (steps). There are two reset TTL inputs, one per 16 channels, with each channel having its own trigger in order to proceed to the next step. This unit is based on 12 bit DACs (Digital to Analog Convertors) which allows to set the voltage with an accuracy of about 2 mV. Other uncertainties taken into account (e.g., noise and

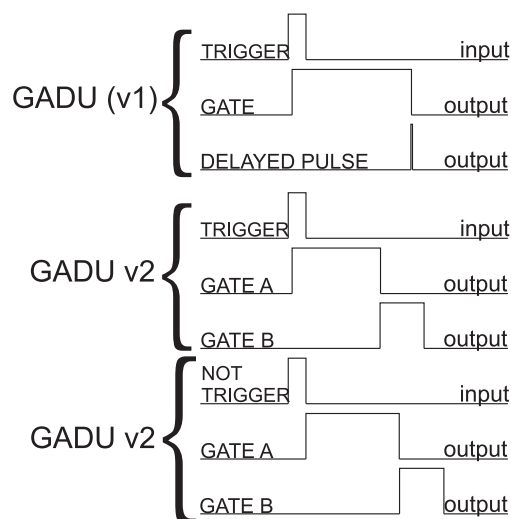


Figure A.5 – Scheme of the input and output signals for the two Gate & Delay Units (GADU). The first one uses only one timing, while the second one requires two timings to be set.

ripple) amount to a final accuracy of about 5 mV. The rise time of this unit is slightly longer than that of the endcap supply, but is still of the order of a few microseconds. Both devices are connected via a USB interface to the computer. This USB device emulates a serial port on the computer. The programs can thus be written as if the devices were connected through a serial port.

The rf signals to perform excitations in the trap are generated by DS345 **frequency generators** from Stanford Research Instruments. Three of these devices are in use at WITCH and all are controlled through a GPIB interface (General Purpose Interface Bus). One is used for the cyclotron excitation with high amplitude to center the ions. If mass purification is necessary, two additional generators are used for the magnetron excitation and a subsequent cyclotron excitation — with a low amplitude.

As the ring electrode of the traps is not always at 0 V, an additional device is needed to combine the RF signals with the DC voltages that are supplied by the trap power supply. This is realized by two home-made NIM modules which do not need to be computer controlled. These units take three inputs: the RF signal, a DC voltage and a gate trigger. Whenever the trigger is high it combines the RF and the DC signal (to a total voltage between -15 and 15 V, which is the limit from the integrated circuits), to give two output signals (RF + DC) with the RF signal phase shifted by 180° relative to the input signal.

The last fast control is the power supply providing the voltages for the spectrometer retardation electrodes; the **retardation power supply**. This device

provides an output voltage from 0 V to above the recoil energy of the isotopes of interest. E.g., for ^{35}Ar which is our primary physics candidate, the recoil energy is 452.6 eV, so a voltage of 500 V is sufficient. This is also a technical limit for the currently used components. The voltage can be changed up to forty times per second, e.g., to ramp from 0 V to 500 V in 12.5 V steps. The voltages and step settings can be changed by a front panel display and numerical keypad or by a computer via a serial interface. There are three main modes: switching from the minimum to the maximum, switching from the minimum to the maximum and back, or a custom pattern. The latter can only be set via computer commands. The exact timing of the voltage changes is crucial for the experiment and is controlled by hardware triggers coming from the main data-acquisition card (Ortec MCS-PCI, see Ref. [Kozlov et al., 2008]). The switching time is of the order of $50\text{ }\mu\text{s}$ and the precision of each voltage step is $\pm 0.1\%$ (from Ref. [Lindroth et al., 2004]). At present this is sufficiently small compared to other systematic effects, as e.g., a broadening of the response function due to the energy of the ions in the decay trap, but in the future this power supply will have to be improved or replaced by one with a better performance.

Slow voltage controls

Besides the fast controls the experiment also needs slow devices to achieve the required conditions for the experiment. These consist mainly of the vacuum system, the voltages on the beamline and re-acceleration electrodes and the control of the superconducting magnets. These controls will be referred to as the slow controls, because in contrast to the fast controls the status of the devices does not need to change within or even between different experimental cycles. Once data-taking has started these parameters are quasi-static and serve to monitor the status of the system. Here we describe the power supplies for the beamline electrodes, with the other slow controls being described in section A.3.3.

Four different power supplies provide the voltages for the beamline and re-acceleration electrodes. Most electrodes only need a maximum of $\pm 2\text{ kV}$; these voltages are provided by two multichannel EHQ F020n power supplies and one EHS F020n power supply, both types from ISEG. Each of these modules has 16 channels. Two channels with good stability ($< 3 \cdot 10^{-5}$) and a voltage around $\pm 2\text{ kV}$ are provided by a dual channel ISEG NHQ234M. Wherever voltages higher (lower) than $\pm 2\text{ kV}$ are required, ISEG CPx supplies with a maximum voltage of $\pm 7\text{ kV}$ and $\pm 10\text{ kV}$ have been used. Finally a power supply for steerer plates, with a central voltage of 0 V is required for which the polarity should be changeable on-the-fly. This unit of specialized electronics was produced in house; it can supply voltages from -2 kV to $+2\text{ kV}$.

Data-acquisition

The experimental set-up contains several data-acquisition devices based on two detection techniques. For diagnostic purposes Faraday cups and micro-channel

plate (MCP) detectors [Coeck et al., 2006] are used; these are being read out by an electrometer and an oscilloscope, respectively, which are both controlled by a GPIB interface. It is also possible to read a signal from the diagnostic MCPs with an MCS-PCI card from Ortec. However, this is in general not done; the MCS-PCI card is reserved to acquire data from the main detection MCP which observes the recoil ions, and is more advanced than the diagnostic MCPs. The data-acquisition electronics for the main detector was described in detail in Ref. [Kozlov et al., 2008] and will not be discussed here.

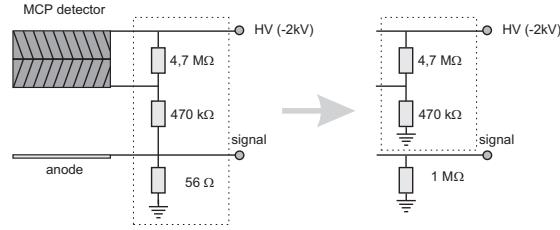


Figure A.6 – Two possible electronics schemes for powering up an MCP and reading out the MCP signal (from [Coeck, 2007]). The output signal for the scheme on the left will show pulses caused by single ions. The output signal for the scheme on the right will remove any timing information from the MCP signal - and thus single ion detection - by the incorporation of a resistor with a high value (1 MΩ in this case).

The usage of a Faraday cup for beam tuning is only possible when the PDT is not involved. The practical detection limit for an electrometer is of the order of 1 pA, which roughly corresponds to 6 million particles per second. This is mainly limited by noise. This number of ions – 6 million – corresponds to a full trap load of REXTRAP and is most of the time not used for tuning. As a consequence it is hard to detect a single ion bunch originating from REXTRAP; this can be solved by using a higher repetition rate¹. Unfortunately this excludes the use of the PDT, the repetition rate of which is currently limited to 5 Hz. As a result, the Faraday cups in the horizontal and vertical beam lines, can only be used to tune the 30 keV ions.

In order to tune the pulsed down low energy ions, the diagnostic MCP detectors in conjunction with an oscilloscope are used. Typically a pulse from an MCP has a length of the order of 10 ns. A bunch of ions is thus not detected as a single pulse, but rather as a series of short pulses. To use these pulses to quantify the number of ions is not so easy with an oscilloscope, whereas it can easily be realized with a scaler and fast electronics. There is, however, a work-around for this; one can use a high resistive termination for the MCP signal (Fig. A.6, right). This amplifies the signal significantly, but the timing information of each single event is lost which can actually be a big advantage during beam tuning. The many short and low-amplitude pulses thus become one long pulse with a large amplitude. This amplified signal can easily be seen on an oscilloscope

¹REXTRAP routinely operates at 50 Hz

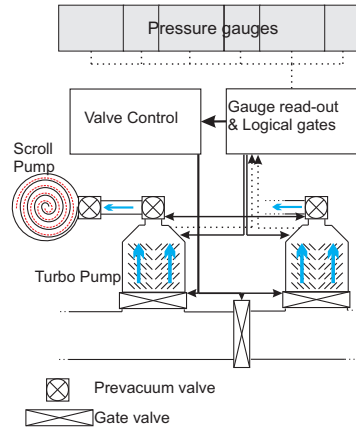


Figure A.7 – Working principle of the WITCH vacuum system. Input signals (dotted lines) are coming from the turbo pumps (i.e., operating or not?) and the pressure gauges. These signals are then processed via logical gates to generate control signals (full lines), e.g., to close a valve if needed.

and used for tuning. The amplitude of the signal is then an indication for the number of ions impinging on the MCP detector. This signal can be acquired and integrated as needed.

Other slow controls

The vacuum system includes pressure gauges, the read-out for these gauges, dry scroll pumps, turbo pumps, gate valves and prevacuum valves (Fig. A.7). Model types of these devices are listed in Table A.1. Currently only the pressure read-outs are fully integrated in the control system, while this is planned for other controls like the control box for the valves (gate valves and prevacuum valves). All devices, except for the scroll pumps which have no communication capabilities, can be controlled by a serial RS232 interface.

There are two types of pressure read-out units in use. TPG262 read-out units are used for full-range gauges and one UHV gauge, that can measure down to 5×10^{-11} mbar. The TPG300 units are used for Pirani and Penning gauges. The implementation of the read-outs in the computer control system is limited to reading back the pressure in the system. Advanced functions, e.g., the definition of the switching functions, are not controlled remotely; this is done on the devices themselves.

The turbo pumps will not be fully integrated in the control system. The only parameters that are convenient to monitor are their rotation speeds, which is useful for diagnostic purposes. The gate valves are used to separate different beamline sections and to separate the turbo pumps from the beam line vacuum when necessary. Prevacuum valves are installed in the tubings between the

turbo and scroll pumps in order to prevent an accidental inlet of air which could damage the turbo pumps and the system. Both types of devices are controlled by a home-made valve control box, which controls whether or not a valve should be open. The user can manually open or close a valve by a switch, but this could also be controlled by computer. As a safety measure a valve will only open when its controlling channel receives a 5 V signal. These signals are generated by a power supply, signals from the turbo pumps, signals from the pressure read-outs and logical gates to combine the previous signals. This arrangement assures a proper handling of exceptional events (power cut, pump failure, etc.) to make sure the vacuum is not breached and pumps are not damaged.

The superconducting magnets are controlled by a power supply from Oxford Instruments. The computer communication is not used here because of the dangers involved when dealing with cryogenics and high currents. The level of both cryogenic liquids (LN_2 and LHe) can be read back on a level meter, via serial communication. Furthermore several resistors are present in the cryostat to give an indication of the temperature at different places in the system. Small modules for resistance read-out are attached to them and can be read out via serial communication. The read-outs of this section are not implemented in the control system yet.

A.4 Architecture of the WITCH Control System

Several constraints need to be considered when choosing the control system for an experiment. For the experimentalist's ease the implemented solution has to be stable, bug-free and easy-to-use. For the developer, who is often also an experimentalist in medium-scale experiments like this one, the system should not be too time-consuming to implement and it should be easy to maintain after the first development phase. Lastly and evidently the control system should be well documented in view of future developers and users.

In the past, a first attempt at the development of a control system was made already [Lindroth et al., 2004]. This system was specifically developed for the WITCH experiment, but unfortunately turned out to be not sufficiently versatile and maintainable. Since the experiment was still in a development phase new devices had to be implemented from time to time. This prompted us to switch to a new control system. We decided for the *CS-Framework* developed by the EE/KS group at GSI [Beck et al., 2004]. WITCH-specific extensions are then built around this core system. This ensures continuous support and information about the control system, i.e., the EE/KS group at GSI and other users of this framework. Currently this community includes other Penning trap based experiments, such as ISOLTRAP [Beck et al., 2004], REXTRAP [Ames et al., 2005], SHIPTRAP [Block et al., 2005], TrigaTRAP [Ketelaer et al., 2008], LEBIT [Ringle et al., 2006], ClusterTRAP [Schweikhard et al., 2003] and HITRAP [Herfurth et al., 2006], and the Phelix experiment [Neumayer et al., 2005].

A.4.1 CS-Framework

DIM

One of the key protocols is DIM (Distributed Information Management), a network communication system originally developed for the DELPHI experiment at CERN [Gaspar et al., 2001]. Today it is the backbone of the communication for LHC experiments. DIM is a light weight protocol based on TCP/IP. It follows the client/server paradigm; the basic concept is a named service. Servers publish their data as services to which clients can subscribe. Whenever a service is updated with new data the subscribed clients receive the updated data. Clients can also send commands to servers, e.g., to send updated data to a service. For transparency and easy recovery from crashes a name server was introduced to keep an up-to-date list of all available services and servers. Since version 3.10 of the *CS-Framework*, DIM was implemented as the communication protocol, which added some extra features and provided increased performance [Beck & Brand, 2007]. The current version of the *CS-Framework* is 3.14.

CS-Framework

The *CS-Framework* can be best described as an object-oriented, distributed and event-driven LabVIEW-based Control System Framework with some SCADA (supervisory control and data-acquisition) functionality, see Ref. [Beck et al., 2004] and [Beck & Brand, 2007]. No other programming language than LabVIEW is used, because it is easy to learn and it provides the necessary tools to design both low-level instrument drivers and high-level graphical user interfaces.

All components are integrated into a LabVIEW program based on communication through DIM. There are some extra programs that offer necessary functionality. An SQL (Structured Query Language) server is used to access a relational database, MS Access in our case, where configuration settings are stored. These configuration settings can contain information about the communication (ports, baud rate, etc.), but also more general features can be stored. E.g., which gauge is connected to which channel of a pressure read-out. Finally there is also a Domain Management System (DMS) that keeps track of the control system entities that are started on the computers in the network, and which also allows for remote control of these entities and other programs. One can for instance configure which programs have to be started automatically on a remote computer, but the DMS can also try to restart the programs when they have crashed.

One needs to start the three server programs (DIM Domain Name Server (DNS), SQL server and DMS server) for the *CS* to work; at WITCH they usually reside on one server computer (Fig. A.8). The client computers in the control system network only need to start the main LabVIEW program (*CS-Framework*) to have full functionality. The DMS functionality also requires the start-up of the DMS client, but this is only necessary when remote start-up of programs is wanted.

The *CS-Framework* is available under the GNU General Public License and can be downloaded from SourceForge [Beck & Brand, 2010]. A link to the online documentation is provided on the SourceForge website.

A.4.2 WITCH-specific device classes

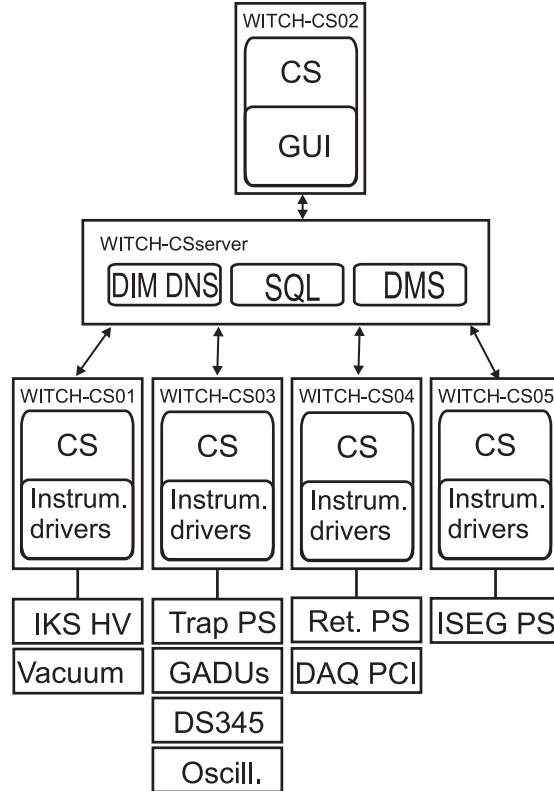


Figure A.8 – Architecture of the *WITCH* control system. Square boxes refer to hardware and rounded boxes refer to software. Computers in control of devices rely on the server for start-up of their CS objects. The arrows indicate the directions of communication; however, this picture is incomplete. GUIs can interact with all the necessary device computers once a DIM service has been registered with the DNS; these paths of communication are not shown to avoid clutter. The different device computers reside in different physical locations to be as close as possible to the hardware they are controlling. This arrangement is the current one but is still prone to changes.

For the *WITCH* experiment a substantial amount of the hardware has been custom-made with attention being paid to the properties of the devices and not so much to the communication protocol used by them. As a result quite

some add-ons were needed which were not included in the core system or had already been developed by other experiments. The drivers for the commercial devices will be released as a package on SourceForge [Beck & Brand, 2010]; it concerns the TPG262/300 vacuum gauges, the power supplies from ISEG and the thermocouple read-out. To integrate an instrument in the control system, one first has to make the instrument drivers which can then be added as a class in the control system.

A.4.3 Graphical User Interfaces for WITCH

Although it is possible to control the various devices with the basic control system, it is advantageous to build some graphical user interfaces (GUI) to facilitate experimental control and to automate certain processes. Currently five of these GUIs specifically designed for the WITCH experiment exist;

- a GUI to regulate the high voltage power supplies (HVControl),
- a GUI to set the parameters for the operation of the ion traps (TrapControl). This includes the two Gate & Delay Units, both power supplies for the trap electrodes and the frequency generators.
- a GUI to scan different parameters in the system (e.g., voltages, frequencies, amplitudes and timings) for optimization and measurements (Scan.GUI).
- a GUI which connects both data-acquisition methods for measurements and to log useful parameters (DAQInterface).
- a GUI to monitor the status of the vacuum system (VacuumMonitor).

These GUIs are completely independent from the device computer. They can be started on any computer in the network that is running the *CS-Framework*. As such they provide the required flexibility. All communication is handled by DIM in that case. In the following more details are given on the different GUIs. Additionally some examples are added to illustrate how the different GUIs have provided more than merely experimental control and how they have contributed to an improved operation of the set-up.

HVControl GUI

The HVControl GUI is the main program needed to tune the voltages for beam transport. It allows the user to set and read back the voltages on all electrodes in a straightforward way. Problem detection for each separate electrode is also possible; this can be necessary for instance when a channel of a power supply trips due to a spark in the system. Additionally, for the full beam tune one also has to control the timing for the beam gate and the PDT in the TrapControl GUI.

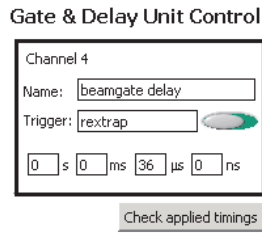


Figure A.9 – One of the 20 identical channels of the panel to control the Gate & Delay unit in the TrapControl GUI. This is a schematic representation of the actual device that can also be operated manually. The 20 identical channels operate as shown in Fig. A.5.

The front panel has a button for each electrode, organized in such a way that it follows a schematic representation of the system. Besides the name of the electrode, these buttons also display the last read back value or set value from the power supply. Other buttons on the front panel provide functionality for saving and loading the settings, to power down all electrodes, to read back the status of all values, to switch between read back/set value on the electrode buttons and to stop the program. There are also panels to control the electrodes, allowing the user to set the voltages. Without too much clicking and/or changing between windows the user can quickly see what effect a specific change in voltage has. There are four of these panels allowing e.g., simultaneous control over the four electrodes of a steerer quadruplet. Finally there is a diagnostics panel where status messages from the different power supply modules can be retrieved.

TrapControl

Whereas HVControl is used to set the voltages of the beamline electrodes, and thus guide the beam into the traps, the TrapControl interface is used to have full control of everything related to the traps. This includes the applied potentials, timings (which are also needed for beamgate and PDT operation) and excitation frequencies and amplitudes. For each of these parts a dedicated subinterface was created. Obviously, all parameters can be saved and loaded to facilitate the operation of the system.

First of all it allows the user to have an intuitive control over the two GADUs (see Fig. A.9). The interface is based on the original GADU. In addition some extra information is available for each channel (i.e., the name of the channel and its trigger).

Secondly, one can control the potentials applied to the trap electrodes. The assignment of the different electrodes to a specific power supply channel is stored in a configuration file. An important tool for working with the traps is the visualization of the actual potentials on the axis of both traps. These realistic potentials are calculated by simulating the electric field for each electrode sepa-

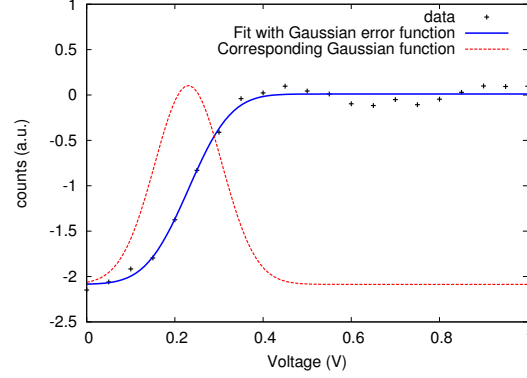


Figure A.10 – Scan of the ion energy with the spectrometer connected to the trap power supply. The data are fitted with an integrated Gaussian fit function (amplitude $\cdot (1 + \text{erf}((x - \mu)/(\sigma \cdot \sqrt{2}))) + \text{background}$), the corresponding Gaussian function (dotted line) being displayed as a reference.

rately (with the simulation toolkit COMSOL [com, 2010]) and by constructing the full potential field as a weighted sum of all potential fields. This provides crucial information during the tuning of the traps, since information on the trap voltages alone is not enough for this.

Finally there is an interface for the DS345 frequency generators. At start-up the program searches for the available frequency generators (as *CS* objects). Once these are found the frequency and amplitude can be set easily.

As an example, the optimization of the traps, which is crucial to provide a radioactive source for the experiment with low energy and a small spatial distribution, was made possible by the TrapControl GUI. The most important process in this optimization is the transfer of ions from the cooler trap to the decay trap. Voltages and timings have to be chosen carefully to avoid energy gain and spatial enlargement of the ion cloud. There is no way around this, since the decay trap does not contain buffer gas in order to avoid scattering of recoiling ions on the rest gas atoms, which would disturb the recoil ion energy spectrum. Optimal ion cloud properties can be carefully tuned by the timing of the transfer and the voltages applied on the traps during these different steps. A scan (made with the Scan.GUI, see next section) of the ion cloud energy is displayed in figure A.10. Shown there is a voltage scan performed with the spectrometer when ejecting the ions from the cooler trap into the spectrometer. This provides the energy distribution of the ions in the cooler trap and the quality of the applied settings. The fit used a normal distribution instead of the expected Maxwell–Boltzmann distribution. The average energy is 0.231(6) eV with a spread (σ) of 0.076(7) eV. When transferring this cloud to the decay trap the energy is slightly increased. The transfer will be optimized further in the near future.

Scan.GUI

The purpose of the Scan.GUI is twofold. On the one hand it can be used to tune the system and to optimize the efficiency by scanning useful parameters. On the other hand it can also be used to obtain useful data and information about the system.

The program has access to experimental parameters like

- the voltage applied to beam line electrodes,
- the timing of the GADU channels,
- the voltage applied to the trap electrodes,
- the frequency of rf excitations and
- the amplitude of rf excitations.

Whereas this GUI can read out the set values, its main purpose is to change these values. Furthermore the program can get data from acquisition devices like an electrometer (for Faraday cup read-out), from an oscilloscope (to read out MCP signals) and from a multichannel scaler (again to read out MCP data). Details of the practical usage of these different acquisition methods can be found in section A.3.3. The program is in effect a sequencer, i.e., it changes the experimental parameters in a stepwise fashion between different cycles and keeps track of the effect this has on the acquired detector signal.

The motivation to develop this program came from the need to improve the tuning of the beam. Prior to the first attempts for a control system for WITCH, the beam tuning was done by changing the voltage applied to a certain electrode and at the same time observing the signal on the electrometer or the oscilloscope. This, however, was a very difficult and time consuming process; in the first place it is cumbersome to change voltages manually, but secondly and most importantly, the signal on the oscilloscope is fluctuating in time due to fluctuations in the intensity of the ion source used. To detect an improvement or degradation of the beam tune was therefore rather hard. By systematically scanning one electrode, trends in the acquired data can easily be spotted. Further, a voltage which yields a maximum in the signal on the detector does not necessarily correspond to the optimal tune. Similar arguments can be applied to the tune of the timing for the beam gate and PDT; often one can find reasonable values by doing a manual tune, but a systematic scan can provide settings that are more stable and more reliable. Additionally, performing two dimensional scans (e.g., see Fig. A.11) is easily done in the Scan.GUI, although it might be time-consuming in some cases, but to do this manually is next to impossible. Systematic scans of the voltages have been performed resulting in a significantly improved transmission efficiency. The hardest part in the tuning is the injection into the magnetic field. In 2004 this was still in the order of 1 % to 10 % (page 30 in ref [Coeck, 2007]), but this has been improved to about 20 % already. In time this number can in principle be further improved to close to 100 % of the initial intensity of the ion bunch from REXTRAP.

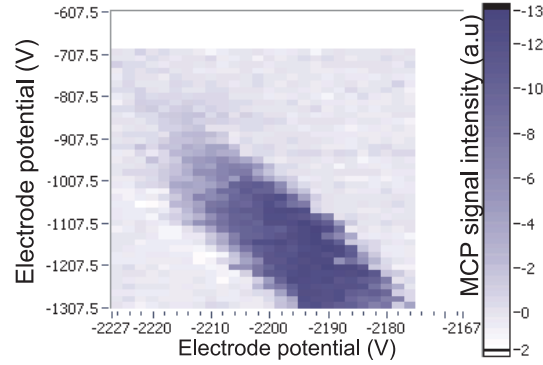


Figure A.11 – Intensity plot of a two dimensional scan of two electrode pairs measured with a diagnostic MCP in the beamline. On the horizontal axis the voltage on the 90° bender is shown, on the vertical axis the voltage on the corresponding kicker. The intensity of the ion beam signal is color encoded; the darker, the higher the intensity.

By including the control of a few other experimental parameters as well, much more than an optimized beam tune can be obtained. The Scan.GUI is e.g., very useful in optimizing the trap cycle. Since the ions in the decay trap act as the scattering-free source for the WITCH experiment, characterization of these ions provides us with valuable physical data. The optimization of the trap cycle includes the determination of the magnetron and cyclotron frequency, finding an optimal cooling time for the ions, getting a good tune for the transfer potential, and trapping the ions in the decay trap in as shallow a potential as possible. The search for the excitation frequencies involves frequency scans to find a resonance in the signal. This characterizes properties of the WITCH Penning traps themselves, i.e., mechanical imperfections and the magnitude of the magnetic field, but can also be used to study space charge effects [Coeck et al., 2007b]. This was necessary in 2007, when the electrodes of both the cooler and decay traps were replaced. These new traps had to be characterized and their performance checked. This was done by determining the mass resolving power of the cooler trap. Three consecutive excitations are used for this; first a quadrupolar excitation to center the ions, then a magnetron excitation to shift them radially away from the trap center and, finally, another quadrupolar excitation to recenter them. All these excitations have to be performed at the correct frequency [Coeck et al., 2007b]. Initially a single ion species is used, but in principle one wants to make use of this mass resolving scheme to remove contaminant ions with mass close to the ions of interest (i.e., isobars and isomers). A mass re-

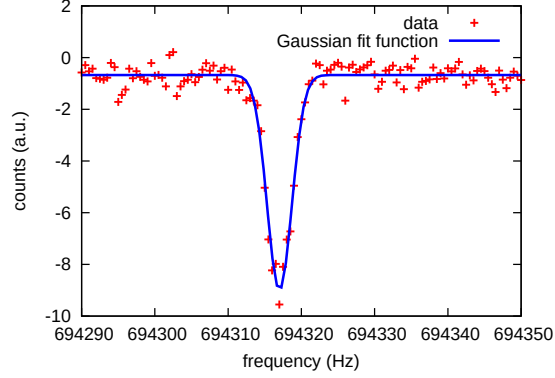


Figure A.12 – Resonance scan of the cyclotron frequency in a mass resolving excitation scheme, obtained with the Scan.GUI. A more negative value on the y-axis indicates a larger MCP signal. The fit function is a normal distribution; the center of the distribution is at 694317 Hz with a standard deviation of 2.4 Hz.

solving power in the order of $m/\Delta m = 10^5$ was obtained for a single ion species (Fig. A.12).

Finally, another useful parameter that can be scanned is the ion energy as shown in the previous section about the TrapControl GUI (Fig. A.10).

DAQInterface

There are two data-acquisition branches at WITCH; a fast scaler branch and a slower branch which gives extra information like position read-out [Kozlov et al., 2008]. The fast branch is read out by a PCI card and is controlled by a commercially available program. This program is started by a LabVIEW routine by means of a batch file. The slow branch is controlled by a custom-made LabVIEW routine. Both routines are started from the DAQInterface GUI to assure synchronization between those two data-acquisition branches. The connection to the control system consists of the logging of experimental conditions that are relevant for the data-analysis (e.g., timings, trap voltages, etc.) when the acquisition of data is started. To this end the program subscribes to the needed DIM services.

VacuumMonitor

The VacuumMonitor is a passive GUI. It subscribes to DIM services that are related to the vacuum system (pressure, status of gauges, turbo pump status, etc.) and displays the data. Currently only the pressures are monitored, but it will be extended to include the status of the valves and the turbo pumps when these devices are integrated in the control system. The data themselves

are also stored in a file. This GUI is useful to check whether everything in the system is working properly. It will be possible to store some additional parameters manually, e.g., the magnetic field, since computer control over the magnet power supply is not included.

This is not superfluous information for a correct operation of the system; due to the installation of non-evaporable getter (NEG) pumping material [Benvenuti et al., 2001] in the system, the control and monitoring of the vacuum system has become crucial to reach a good vacuum around $1 \cdot 10^{-9}$ mbar. In the event of a power cut, it needs to be checked whether the sections with the NEG materials have been correctly closed off to avoid saturation of the material. Also, the source of other unexpected device failures can be more easily traced by a constant monitoring of system parameters.

A.5 Conclusion and Outlook

A first fully operational version of the control system for WITCH is now available. A next important step will be to further improve and consolidate it.

In addition, one of course also wants to be able to implement new devices in this control system. Indeed, although the WITCH set-up is now fully operational, extra features will certainly still be added to further improve and extend it. This has to be done both on the low-level instrument drivers as the high-level GUIs. Instrument drivers can be tweaked and performance can be improved. As an example, in the meantime the computer card responsible for the CanBUS communication has been replaced by a card recommended by the power supply manufacturers. Since this card matches more closely the communication requirements of the power supplies, the read-out speed for the power supplies has been increased by an order of magnitude, extending the ease-of-use of the HV-Control GUI. Another example is an FPGA (Field Programmable Gate Array) as a pulsed pattern generator to replace the GADU. The full implementation of the FPGA card was particularly easy thanks to the work of the *CS* community.

Also the error handling can be done in a more transparent way. Experience with the existing and new hardware will allow to find the best suited devices concerning both flexibility in use and reliability in computer communication. For instance, the implementation of a Keithley 2410 is under way to replace the home-made retardation power supply. This new device extends the voltage range and the precision of the applied voltages on the spectrometer.

On the high-level end the GUIs can still be improved by making them more user friendly and adding new features. The Scan.GUI could for instance be synchronized by triggers with the experimental cycle to optimize its efficiency and speed. In the end all this will contribute to a more smooth operation of the system and increased efficiency.

A.6 Acknowledgements

We would like to thank the electronics workshop of the physics department at the K.U.Leuven for making all the devices with special requirements we have asked for, as well as the colleagues from the REXTRAP & ISOLTRAP set-ups at ISOLDE.

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A.7 Additional comments

Since the WITCH control system is a continuously evolving collection of software and hardware, some changes have already been made since the article went into print while other changes are planned for the near future. This section will list these changes and, for completeness, it will also add details for the user and the developer which were not included in the article.

A.7.1 New Hardware

FPGA

An FPGA card (Field-Programmable Gate Array) is an integrated circuit board that consists of many logical blocks. The connection between blocks is programmable so that an FPGA can have many applications. Two applications of an FPGA are available as *CS* classes already; a multichannel scaler (MCS) and a timing unit.

The Gate & Delay Units at WITCH is being phased out in favour of an FPGA card. The main advantage of the FPGA card over the GADU is that the wire clutter is removed and as such it is much easier to get an overview of the entire timing scheme, without having to look at the hardware. This will facilitate the training of people new to the experiment, and avoid mistakes in the wiring of the GADU. The properties (resolution, jitter, etc.) of both devices are similar. The FPGA has some minor disadvantages over the GADU. Most importantly, the FPGA is implemented as a state machine in the *CS*, meaning that if one wants to perform a scan of a certain timing parameter one has to stop the FPGA, load the new timing configuration and restart the FPGA, whereas in the GADU each channel can be modified individually. The time needed to complete a timing parameter scan might therefore take longer; this will depend on the exact implementation of the device in the Scan.GUI. Also, independent operation of the cooler trap and decay trap - e.g. to start loading the cooler trap while some action is still ongoing in the decay trap - requires major rethinking.

Keithley 2410

The power supply for the retardation electrodes in the spectrometer needs to meet certain requirements.

- High precision and accuracy; 0.1 V over the full voltage range, see figure 6.6.
- A range from 0 to 800 V would be required to measure ^{35}Ar , which has an endpoint close to 500 V, thus allowing a measurement of the background above this endpoint.
- The time required to change from one voltage to another should be sufficiently short as the longer this takes the more statistics are lost; 100 μs is

set forth as an upper limit. If time bins of 10 ms are used (which is rather short) during the measurement only 1 % of statistics will be lost.

- The power supply should be able to deliver a current of a few milli-amperes as it is connected to a voltage divider, with a total resistance of 508 k Ω , which is then connected to the different retardation electrodes.

The ‘old’ retardation power supply was lacking in accuracy/precision and range. It was not possible to extend this range easily because the integrated circuits were not available for this. Also, for a precision measurement with ^{35}Ar the potential in the analysis plane should be known to high precision and accuracy (see section 6.1.2). A promising candidate for a new retardation power supply is the Keithley 2410. It has a precision of 50 μV , a range up to 1.1 kV, a rise time of 0.5 V/ μs and a stabilisation time of 100 μs to reach 0.1 % precision. Moreover, due to the nature of the device as a sourcemeter, it can easily deliver the required currents.

A.7.2 New Implementation

ISEG power supplies

The communication with the ISEG power supplies was unstable from time to time. Closer investigation of all the software and hardware involved exposed some issues. First of all, the CanBUS card to communicate with the power supply seemed to have been of the wrong type. The CanBUS protocol exists in a few variations; there is a low-speed/fault-tolerant one, but there is also a high-speed one. The card in use when the article was written was a low-speed/fault-tolerant card from National Instruments. The suspicion was that this card was causing the problems, as ISEG recommends (high-speed) CanBUS cards from PEAK-Systems. A card from PEAK-Systems was thus ordered to test this. Currently it works and, as an added bonus, the communication speed with the power supplies is greatly increased which will improve the HVControl interface. As an example; with the old card and drivers it was only possible to read back the voltage from 6 channels per second, while the read-out of one channel takes less than 10 ms with the new card. The implementation of this new card and drivers was done by a CERN summer student, Ashish Naik [Naik, 2010].

A.7.3 New GUIs

DAQInterface

The two branches of the data-acquisition have been combined into one program. This interface is not implemented according to the usual *CS* philosophy. The instrument drivers of the MCS-PCI are addressed directly by the GUI, while usually the communication happens through the network via the aid of DIM.

The reason for this is that the fast scalar branch uses a program from the manufacturers, which is started by a batch file created in LabVIEW. The interface for the slower, event-by-event branch communicates directly with the instrument drivers. Whenever a measurement is started on the scalar branch, also the measurement of the event-by-event branch is started. Additionally, all parameters of the system (i.e. voltages, frequencies, timings, etc.) are also stored. All data is stored on the server of the WITCH CS network.

VacuumMonitor

A GUI showing a complete overview of the WITCH vacuum system has been made. Pressures used to be stored in a simple logger program. Now, a more graphical GUI is operational which also includes the status of the valves. Other items that can still be implemented are the status of the turbo pumps, the levels of the cryogenic liquids, the status of the magnets, a thermocouple read-out for certain components of the system and the status of the UPS devices.

A.7.4 Technical details

For completeness, technical details of the code are outlined in the following.

HVControl GUI

The program consists of six threads running in parallel. The main thread handles all events from the front panel. There are four threads for each of the panels to control the electrode objects. The last thread serves to prevent that the user has to wait for the completion of certain events. For instance, when all electrode voltages are being read out (this typically takes 10–20 seconds) the user still has access to the front panel. This way the user can abort the read-out of voltages. The threads communicate with each other through the use of *notifiers* and *message queues*. In practice the communication goes in one direction; the main thread tells the other threads what to do based on the events it has received.

The main thread consists of an *event structure* embedded in a *while loop*. The *time out event* checks for newly created electrode objects in the control system network. The other events in the event structure are triggered by buttons or mouse clicks on the front panel (e.g. to close the open front panel of an electrode) and can give commands to the other threads in the program (e.g. when opening the panel of an electrode).

The threads that encapsulate the subpanel functionality are *while loops* waiting for an element from a *message queue*. When no element is received through the *message queue*, the voltage of the electrode is read out. Elements in the *message queue* control voltage changes, the opening and closing of the subpanel.

TrapControl GUI

This GUI is purely event-driven, i.e., it waits for input of the user to perform a certain action. The structure of the program is fairly simple; the main program consists of an *event structure* embedded in a *while loop* and no actions are undertaken for the time-out event. In spite of its simplicity, quite some functionality is implemented in this GUI.

Scan.GUI

The program consists of two threads. The first, event-driven thread (i.e., the main thread) is used to set up a scan and to display the acquired data. The second thread is a sequencer that handles the correct change of experimental parameters and the data-acquisition.

The main thread needs the input of a *subVI*² for the configuration. That *subVI* has been introduced to remove clutter from the main program. When the configuration data are received, the main thread is ready to start the scan. Some parameters as e.g. a waiting time between two scan cycles and the number of passes, can be set. When the scan is started, the second thread takes over. Since the scan is running in a parallel thread it is still possible to perform actions in the main thread (e.g. inspecting previous data, aborting the scan, etc.). Communication between the threads goes in both ways. The main thread can tell the scan to abort. But the scan thread can send new data from the scan back to the data display of the main thread.

²a *subVI* is a subroutine in the LabVIEW programming environment and is equivalent to a function, subroutine or method in other programming languages.

Appendix B

Penning Traps

In this appendix Penning traps are briefly discussed as they play an important role at WITCH as the holders of the scattering-free radioactive ion source for the experiment. The basics of Penning traps are explained and how ions can be manipulated in such traps. The current implementation of the WITCH Penning traps is presented afterwards. Finally, it is shown how the operation of the traps needs to be optimised for accurate measurements at WITCH.

B.1 Basic Penning Trap Theory

The Penning trap is an electromagnetic trap first developed by H. G. Dehmelt [Dehmelt, 1958]. He got inspiration from the ion vacuum gauge built by F. M. Penning, the so-called Penning gauge [Penning & Nienhuis, 1949, Penning, 1939]. The first usage of the Penning trap was to measure the g-factor of the electron [Wineland et al., 1973]. But soon other possibilities for such traps were envisaged. Now Penning traps are routinely used in chemistry, atomic physics and nuclear physics. All kinds of charged particles have been trapped already, ranging from electrons to molecules and clusters, radioactive ions and even antiparticles such as positrons and antiprotons.

A Penning trap consists of a strong static magnetic dipole field;

$$\mathbf{B} = B \cdot \mathbf{e}_z \quad , \quad (\text{B.1})$$

and an electrostatic quadrupole field;

$$\mathbf{E} = \frac{U_0}{2d^2}(x\mathbf{e}_x + y\mathbf{e}_y - 2z\mathbf{e}_z) \quad , \quad (\text{B.2})$$

where $\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$ are perpendicular unit vectors, U_0 is the potential between the ring and endcap electrodes and $d = \sqrt{(z_0^2 + \rho_0^2/2)}/2$; see Fig. B.1. Basically the magnetic field ensures radial confinement and the electric field axial confinement.

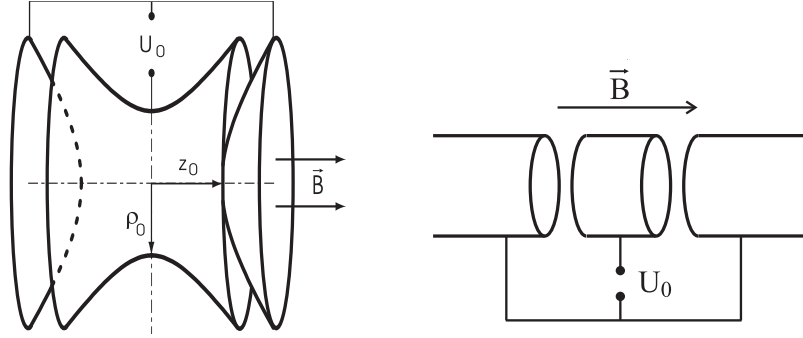


Figure B.1 – Left: A hyperbolic Penning trap. **Right:** A simple example of a cylindrical Penning trap. Note that the true field of a Penning trap given in Eq. B.2 is only realised in a small area around the center of both traps.

B.1.1 Single Particle Motion in a Penning Trap

The motion of a single particle in an ideal Penning trap can be solved analytically. The full derivation can be found in Ref. [Brown & Gabrielse, 1986]. Here only a short summary, necessary for a good understanding of fundamental properties of ions in a Penning trap, is given.

The motion consists of three independent *eigen*motions, see figure B.2;

$$\begin{aligned} z(t) &= A_z \cdot \cos(\omega_z t + \phi_z) \\ x(t) &= R_+ \cdot \sin(\omega_+ t + \phi_+) - R_- \cdot \sin(\omega_- t + \phi_-) \\ y(t) &= R_+ \cdot \cos(\omega_+ t + \phi_+) - R_- \cdot \cos(\omega_- t + \phi_-) \quad , \end{aligned} \quad (\text{B.3})$$

with $\omega_z, \omega_{\pm}$ given by Eq. B.4 and Eq. B.5, ϕ_z, ϕ_+, ϕ_- are arbitrary phases and A_z, R_+, R_- are the amplitudes of the respective motions. The motion in the z -direction is an harmonic oscillator motion with angular frequency

$$\omega_z = \sqrt{\frac{qU_0}{md^2}} \quad (\text{B.4})$$

in the electric field from Eq. B.2. The radial motion consists of two independent motions; the magnetron motion at angular frequency ω_- and the cyclotron motion at angular frequency ω_+ . These two angular frequencies are given by

$$\begin{aligned} \omega_{\pm} &= \frac{1}{2} \left(\omega_c \pm \sqrt{\omega_c^2 - 2\omega_z^2} \right) \\ \omega_c &= \omega_- + \omega_+ = \frac{qB}{m}. \end{aligned} \quad (\text{B.5})$$

The cyclotron motion is the usual motion of a charged particle in a magnetic field. However, in a Penning trap its frequency is slightly modified from $\nu_c -$

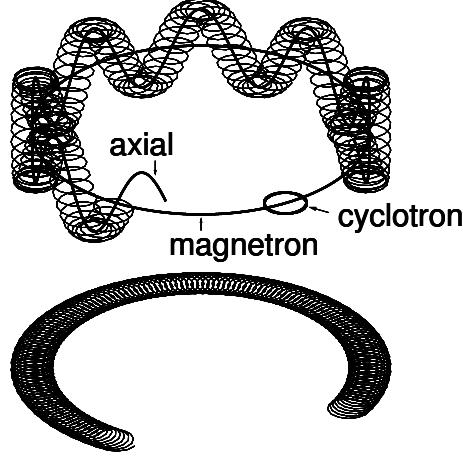


Figure B.2 – The motion of a charged particle in an ideal Penning trap consists of three separate motions: the axial motion, the magnetron motion and the cyclotron motion. The full motion (**top**) and a projection of the motion (**bottom**) in the radial plane are shown. Taken from [Coeck, 2007].

the cyclotron frequency – to ν_+ – the reduced cyclotron frequency – due to the presence of the electric field. The harmonic oscillation and the cyclotron motion are stable motions; upon reducing total energy their amplitude will be reduced. The magnetron motion is not stable; when losing potential energy the ion will move radially away from the centre of the trap, which will increase its kinetic energy. This is because the electric field points outward at the trap centre. The following relations exist between the frequencies of the eigenmotions of ions in a Penning trap;

$$\nu_c \approx \nu_+ \gg \nu_z \gg \nu_- \quad . \quad (\text{B.6})$$

As the cyclotron and axial frequency are much larger than the magnetron frequency, it is clear that their respective motions will lose their energy – e.g. due to buffer gas collisions – much faster than the magnetron motion.

$$\begin{aligned} \omega_+ + \omega_- &= \omega_c \\ \omega_- &\approx \frac{U_0}{2Bd^2} \end{aligned} \quad (\text{B.7})$$

B.1.2 Excitations

The motion of an ion in a Penning trap can be altered by applying radiofrequency (rf) fields, this will be referred to as an rf excitation. To this end the ring electrode (the central electrode) must be segmented, see figure B.3.

During a dipolar excitation a time-varying dipole electrical field is superimposed

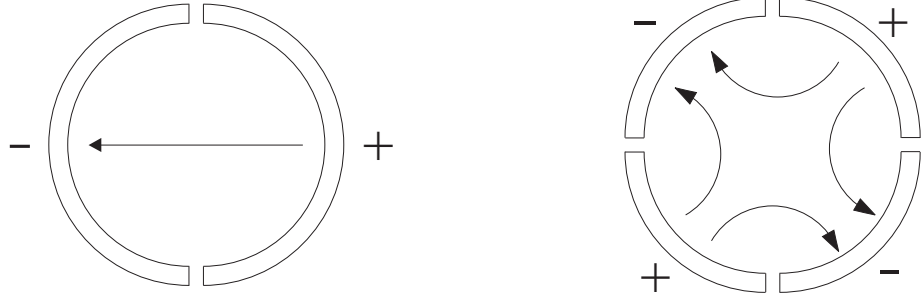


Figure B.3 – Segmentation of the ring electrode required to apply dipolar and quadrupolar excitations. The arrow indicate the direction of the electric field gradient due to applied excitations. Also, due to the shapes of the depicted trap electrodes, only in the centre of the traps the correct fields are generated. Indeed, an ideal dipole field for instance, can only be generated by two infinitely large parallel plates. Taken from [Coeck, 2007].

on the trap potential;

$$\mathbf{E}_d(t) = \frac{U_{rf}}{\rho_0} \cos(\omega_{rf}t + \phi_{rf}) \mathbf{e}_x. \quad (\text{B.8})$$

A quadrupolar excitation is achieved with the following field;

$$\mathbf{E}_q(t) = -2 \frac{U_{rf}}{\rho_0^2} \cdot \cos(\omega_{rf}t + \phi_{rf}) \cdot (y\mathbf{e}_y - x\mathbf{e}_x), \quad (\text{B.9})$$

where ω_{rf} , ϕ_{rf} and U_{rf} denote the angular frequency, phase and amplitude of the excitation, respectively, and ρ_0 is the trap radius as shown in figure B.1.

These excitations can be used to manipulate the ions in the following ways;

- A dipolar excitation at the magnetron frequency ν_- will increase the magnetron radius of the ions, thus lower its potential energy, but increasing the kinetic energy of the motion. In other words; the ions (or ion cloud) is moved away from the trap centre. Because ν_- is to first order mass independent it will remove all ions from the trap centre, irrespective of their mass.
- A dipolar excitation at the reduced cyclotron frequency ν_+ will have the same effect as a dipolar excitation at the magnetron frequency ν_- . The difference lies in the applied frequency; ν_+ is mass-dependent and thus it will only remove ions with a given mass from the trap centre.
- A quadrupolar excitation at the cyclotron frequency ν_c will couple the magnetron and the cyclotron motion, thus periodically converting one motion into the other and *vice versa*. If buffer gas is present in the Penning trap this will result in the centring of the ions; this cooling technique is an example of sideband cooling.

More excitations can be performed in a Penning trap – e.g. octupolar excitations or axial excitations –, but these will not be discussed here. In section 4.2.4 it will be shown how the excitations are applied at the WITCH experiment.

B.1.3 Deviations from Single Particle Motion

The picture of the single particle motion presented until now is far from complete; different disturbances can cause this motion and the corresponding excitation frequencies to change. The main deviations from these analytical equations of motion are described in the following.

Buffer gas

Penning trap-based experiments often consist of several Penning traps to manipulate the ions in successive steps. Also at WITCH the first trap, referred to as the cooler trap, is used for preparing the ions. In this trap a buffer gas is present, the purpose of which is to remove kinetic energy when the ions are injected into the trap and to centre the ions when a quadrupolar excitation is applied. The detailed trapping cycle is described in subsection B.2.2.

Buffer gas will obviously modify the equations of motion of a particle in a Penning trap [Savard et al., 1991]. When the buffer gas is modelled as a Stokes damping force analytical solutions for the equations of motions can still be obtained as shown in Ref. [Coeck, 2007, Chapter 5]. Buffer gas collisions are more realistically treated in simulations where the process of a collision between the ion and the buffer gas is modelled as a hard sphere collision [Schwarz, 2006].

Many particles

The WITCH experiment aims to have 10^6 ions in its Penning traps. Because of the electrostatic repulsion between the ions the motion will be different and the ion cloud will react differently to applied excitations compared to a single particle. The exact behaviour of ions in such conditions are not well understood yet; an ion cloud with one million particles sits between the one particle regime and the plasma regime, for which analytical solutions can be found. To understand large ion clouds one needs to resort to numerical methods combined with experimental observations. Simulations have been undertaken already [Beck et al., 2001, Coeck et al., 2007b], but until now they are limited by the available computation time. The bottleneck in these simulations is the calculation of the Coulomb interaction between the particles in the ion cloud since the simulation time scales as $\mathcal{O}(n^2)$ with n the number of simulated particles. Progress has been made by using approximations [Barnes & Hut, 1986, Carrier et al., 1988, Dubin & O’Neil, 1988, Beck et al., 2001] or by using faster computational methods [Van Gorp et al., 2011].

A well-documented example of the different behaviour of an ion cloud compared to a single particle is a quadrupolar excitation to centre the ions. For one particle

this excitation is performed at ω_c , but for an increasing amount of particles the response of the ion cloud shifts to higher frequencies [Ames et al., 2001].

More important for the WITCH is the exact shape of the ion cloud after the complete cooling process. Because of the Coulomb repulsion between the ions the ion cloud cannot be centred into one single point. The exact shape of the ion cloud, but also the energy distribution, is of utmost importance for the data analysis of measured recoil spectra (see section 6.1.1).

Mechanical imperfections

For WITCH mechanical imperfections in the traps will not distort the measured spectrum, but in other Penning trap experiments where frequencies need to be determined very precisely (e.g. for mass measurements) these distortions have to be taken into account [Brown & Gabrielse, 1986, Gabrielse, 2009].

The main mechanical issue for WITCH is a misalignment of the magnetic and electrical field in the trap. If the centre of the cooler trap, the pumping diaphragm and the decay trap are not connected via the same magnetic field line, ions in the centre of the cooler trap will not end up in the centre of the decay trap after transfer. This will induce a systematic uncertainty in the final recoil ion energy spectrum.

B.2 The WITCH Penning Traps

In this section the design of the WITCH Penning traps will be presented. First some construction details of both traps are given. Then a typical experimental cycle is explained, along with the electronics required to realise this. Finally, the optimisation of the traps is described.

B.2.1 Design

At WITCH the double Penning trap system consists of two cylindrical traps; the first one can be filled with buffer gas and is called the cooler trap, the second one, which holds the radioactive source for the measurement, is the decay trap. The design of both traps is based on the preparation trap used in ISOLTRAP [Raimbault-Hartmann et al., 1997]. A technical drawing of both traps can be found in figure B.4. Both traps are located within the bore tube of a superconducting 9 T magnet with a magnetic field homogeneity of $\delta B < 10^{-5}$. With 20 V applied to the endcap electrodes, the characteristic trap parameter used in the previous section is $U_0/d^2 = 1.8 \cdot 10^4 \text{ V/m}^2$ (or $d^2 = 1/30 \text{ m}$); this parameter does not have the same straightforward geometric meaning as is the case with a hyperbolic trap. This parameter – and thus ν_- (Eq. B.5) – scales linearly with the voltage U_0 applied to the endcap electrodes. The excitation

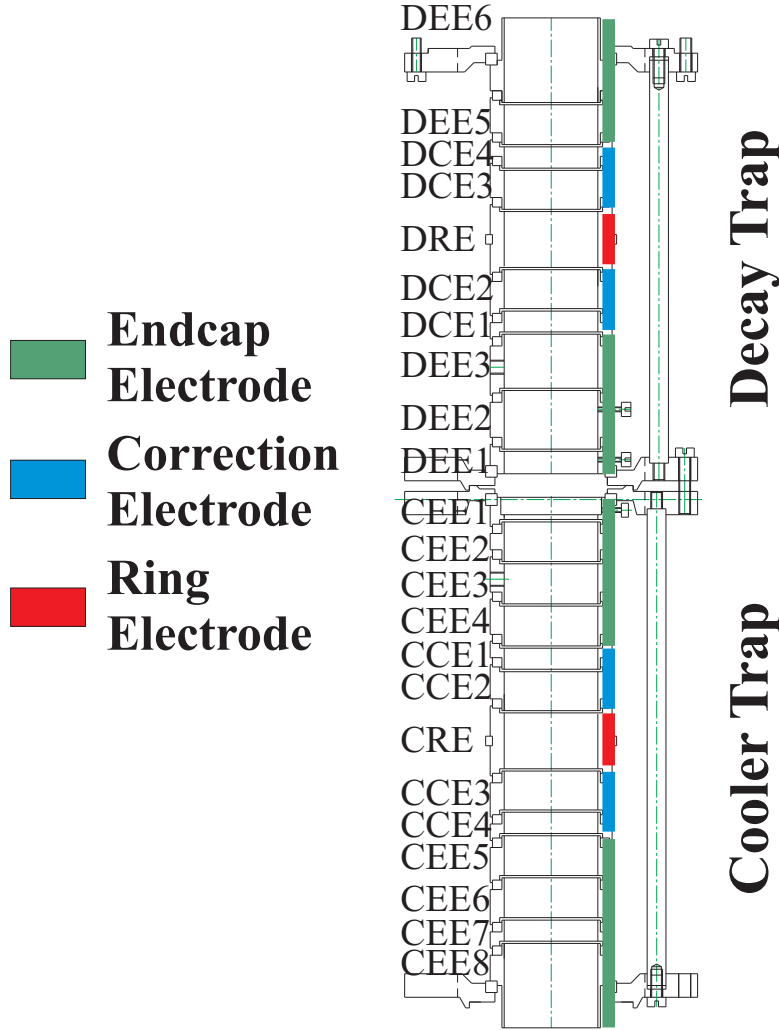


Figure B.4 – Technical drawing of the trap structure and the trap electrodes. In the abbreviations used for the trap electrodes, ‘EE’ refers to endcap electrode, ‘CE’ to correction electrode and ‘RE’ to ring electrode. The lower trap is the cooler trap – where buffer gas can be inserted through a hole in CEE2 – and the top trap is the decay trap. Note that the pumping diaphragm between the cooler and decay trap is not shown in this drawing. The decay trap is slightly shorter than the cooler trap; this was required so that the areas with good magnetic field homogeneity ($\delta B < 10^{-5}$) coincide with the centres of the ring electrodes. The trap electrodes consist of copper with a silver coating – nickel in the latest version – and a gold coating on the surface. The electrical insulation consists of macor rings and the trap structure itself is made out of titanium. All materials used are non-ferromagnetic – except for the small nickel layer and the buffer gas line made of stainless steel (316L).

Table B.1 – Voltages applied to the trap electrodes of the cooler trap and decay trap to obtain a quadrupole potential (based on Ref. [Raimbault-Hartmann et al., 1997]). A typical voltage for the endcap electrodes of the cooler trap is 15 V (= 100 %) and for the decay trap it is typically lower than 2 V. The abbreviations denote; *EE*: endcap electrode, *CE*: correction electrode, *RE*: ring electrode. In the case of the cooler trap, *x* in *EE_x* can be 1–8, in the case of the decay trap 1–6.

Electrode	Trapping voltage (%)
<i>EE_x</i>	100
CE4	67.5
CE3	16.5
RE	0
CE2	16.5
CE1	67.5
<i>EE_x</i>	100

frequencies for a single $^{39}\text{K}^+$ ion in a 9 T magnetic field are:

$$\begin{aligned}
 \nu_c &= 3.547020 \text{ MHz} \quad , \\
 \nu_+ &= 3.546861 \text{ MHz} \quad , \\
 \nu_z &= 33.60136 \text{ kHz} \quad , \\
 \nu_- &= 159.16 \text{ Hz} \quad .
 \end{aligned}$$

A quadrupole potential in the centre of the trap is assured when the ratio between the voltages applied on the electrodes is as shown in table B.1. Note that in that configuration the centre of the trap is not at 0 V, but at a slightly higher voltage. This is compensated for in the control system; see section A.4.3. Possible potentials applied during the transfer of the ion cloud are given in section 4.2.4.

B.2.2 Trapping Cycle

This section describes the part of the experimental cycle that concerns the operation of the Penning traps. A schematic overview of the trap cycle is shown in Fig. B.5.

- a) The ion bunch arrives in the cooler trap. Its energy is typically of the order of 100 eV. The voltage on the lower endcap electrode of the cooler trap (CEE8) is kept below 0 V, while the voltage on the upper endcap electrode (CEE1) is set to a value high enough to reflect the ions. Typically this is 100 V, but depending on the tuning this can be lowered to around 50 V.
- b) When the complete ion bunch is in the cooler trap, the voltage on the lower endcap electrode (CEE1) is raised to the same value as CEE8. Delay times for this are of the order of 30 μs . It has to be noted that due to the different geometry of the two endcap electrodes, CEE8 needs to be

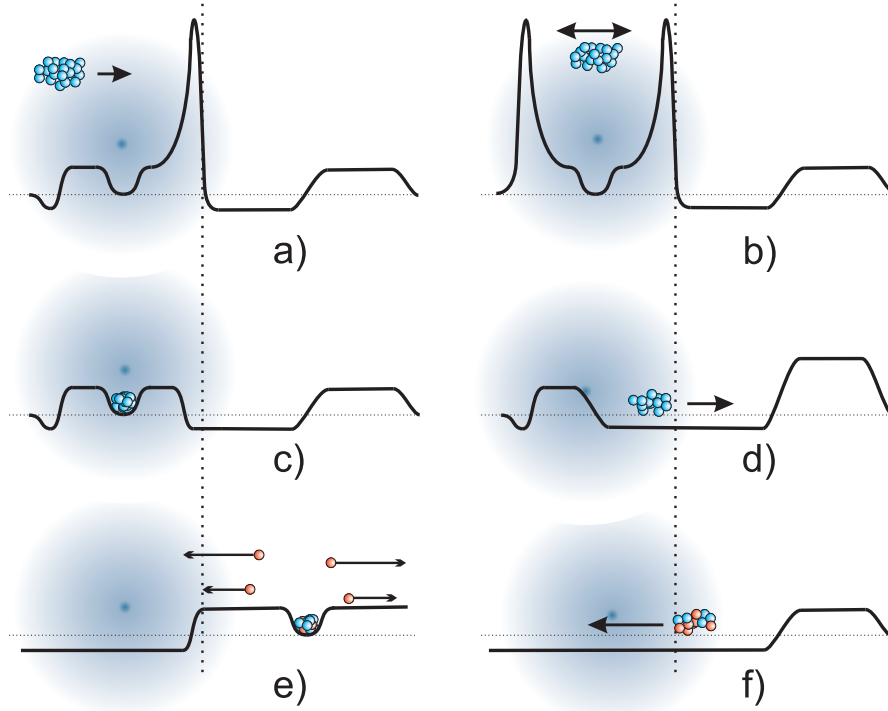


Figure B.5 – A typical trap cycle at WITCH where the full line represents the electric potential in the trap and the dotted line is the separation between (left) the cooler trap and (right) the decay trap. Ions from ISOL-DE/REXTRAP are represented by blue (light) spheres, the red (darker) spheres are ions that have decayed already.

at a slightly higher value than CEE1 to have the same potential along the symmetry axis of the cooler trap. With the ion bunch trapped in the cooler trap the axial kinetic energy will be removed due to collisions with the buffer gas.

- c) The voltages on the endcap electrodes are lowered when the ion bunch has lost enough energy to be trapped in the quadrupole potential of the cooler trap. The required time for cooling into the quadrupole potential depends on the pressure of the buffer gas in the cooler trap; typically this takes about 100 ms. At this point excitations can be applied to centre the ions or to do a mass selective purification. A centring with the help of a quadrupolar excitation at ω_c is routinely performed ($t_{\text{exc}} \approx 50$ ms), while a mass selectively purification is optional. During this time the axial kinetic energy is constantly being carried away by buffer gas collisions. After the necessary excitations, a short cooling period can be inserted again to remove as much – mainly axial – kinetic energy from the ions as

possible.

- d) After the preparation of the ions in the cooler trap they are transferred to the decay trap. This is realised by changing the voltages in the cooler and decay traps. The transfer potential should be tuned to send the ions from the cooler trap into the decay trap without changing the properties of the ion cloud; i.e., the energy and position spread of the ions should remain the same. This can be realised by a Wiley–McLaren type potential [Wiley & McLaren, 1955] (see section 4.2.4). A low energy with a small energy distribution of the ion cloud is required in the decay trap to avoid energy broadening of the recoil energy and thus assure a narrow response function. During the transfer it is good to keep the voltage on the upper endcap electrode of the decay trap at a slightly higher value (for about $100\ \mu\text{s}$) than the final voltage for trapping to avoid that ions with higher energies (i.e. ions that were not cooled sufficiently) can make it into the spectrometer.
- e) At this point the ions are situated in the decay trap. As such the ion cloud is the scattering-free radioactive source for the measurement. Recoil ions that are created in the β decay process with enough axial kinetic energy to overcome the trapping potential (of the order of 1 V) are guided by the magnetic field lines upstream to the cooler trap or downstream into the spectrometer. To the lower endcap electrode of the decay trap (DEE1) a high voltage can be applied to reflect ions with an momentum directed away from the spectrometer into the spectrometer. Typical storage and measurement times are of the order of seconds.
- f) When the measurement is over the ions remaining in the decay trap are ejected upstream through the cooler trap to avoid radioactive contamination of the spectrometer and detector. Some radioactive ions can, however, also be deposited on the pumping diaphragm where they can contribute to the background signal. Note that when no recoil measurement is being performed the ions can also be ejected downstream to tune the system; e.g. to measure the efficiency for different trap settings.

To achieve this combination of different timings and voltages, specific hardware was designed for WITCH. This is described in the next section.

B.2.3 Trap Electronics

The main components of the trap electronics are timing units, power supplies and frequency generators. A schematic overview of how these devices are interconnected is given in Fig. B.6. More details about the electronics can be found in sections A.3.3 and A.7.1 which are part of the chapter describing the WITCH control system. The central device for the operation of the trap electronics is a timing unit. This used to be the Gate and Delay Unit (GADU), but this device is gradually being replaced by an FPGA card (Field Programmable Gate Array). Both devices have similar properties – i.e. resolution and accuracy –

but the FPGA card has the advantage that it is easier to keep an overview of the complete experimental situation. These timing units serve to trigger the two power supplies for the traps (one providing voltages between -15 and 15 V and one delivering higher voltages for the endcap electrodes), and to trigger the frequency generators. The rf signals are combined with the trap potentials by a so-called *RF switch box*.

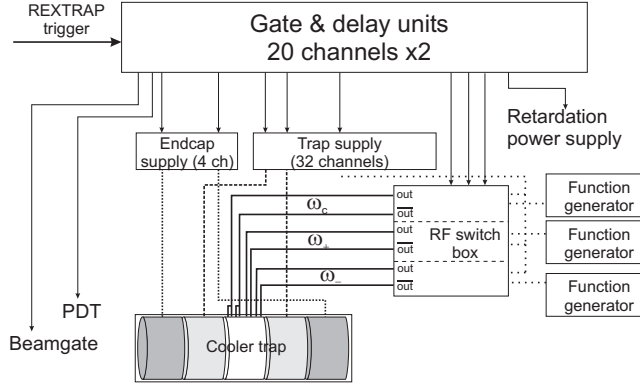


Figure B.6 – *Electronics scheme of the fast controls needed for the operation of the traps.*

Appendix C

Simulations for the Investigation of Systematic Effects

In this appendix the method of quantifying the influence of the different systematic effects on the determination of a is documented. To this end recoil ion energy spectra were generated that included disturbances to model systematic effects. The method of modelling each systematic effect is described here for future reference. The generated spectra were analysed in some cases by an analytical expression for the recoil ion energy spectrum and in most cases by Monte Carlo spectra generated for different values of a . The latter is similar to what will be done during the data-analysis of measured spectra.

C.1 Spectrum Shape

In Ref. [Kofoed-Hansen, 1954] the distribution function, P , in β decay is derived in terms of the recoil energy, T_r , and the β energy, E_β . Neglecting the Fierz interference term b , this results in:

$$P(E_\beta, T_r) dE_\beta dT_r = \frac{M}{2} F(Z, E_\beta) \left[E_\beta p_\nu + \frac{a}{2} (2MT_r - p_\beta^2 - p_\nu^2) \right] dE_\beta dT_r \quad , \quad (\text{C.1})$$

with $F(Z, E_\beta)$ the Fermi function which is set to unity in the following, the neutrino momentum p_ν , the β - ν angular correlation a , the mass of the daughter nucleus M and the momentum of the β particle p_β . Natural units have been used in this expression: $\hbar = c = m_\beta \equiv 1$. SI units can be re-inserted, assuming a negligible (anti)neutrino mass;

$$P(E_\beta, T_r) dE_\beta dT_r = \frac{M}{2} F(Z, E_\beta) \left[E_\beta (E_0 - E_\beta) + \frac{a}{2} (2Mc^2 T_r - E_\beta^2 + m_\beta^2 c^2 - E_0^2 + E_\beta^2) \right] dE_\beta dT_r \quad (\text{C.2})$$

An expression for the recoil ion energy spectrum is then obtained by integration;

$$P(T_r)dT_r = \int P(E_\beta, T_r)dE_\beta dT_r \quad (\text{C.3})$$

Due to conservation of momentum, the energy of the β particle is constrained by

$$\begin{aligned} E_\beta &= \frac{(E_0 - \sqrt{2MR})^2 + 1}{2(E_0 - \sqrt{2MR})} \\ E_\beta &= \frac{(E_0 + \sqrt{2MR})^2 + 1}{2(E_0 + \sqrt{2MR})} \quad , \end{aligned} \quad (\text{C.4})$$

which also serves as the limits of integration for equation C.3. Equation C.3 is an expression for a differential recoil ion energy spectrum. To obtain the spectrum shape that is measured during an experiment at WITCH, one more integration has to be performed;

$$P_I(R) = \int_{T_r=R}^{T_r=R_0} P(T_r)dT_r \quad , \quad (\text{C.5})$$

with R the recoil ion energy, and R_0 the endpoint energy of the recoil ion energy spectrum. This equation can be worked out explicitly and analytically, but it is a very complicated expression.

C.2 Simulation Principle

Spectra can be generated using the distribution function of equation C.3 and the acceptance–rejection method. This way random energies can be generated according to a differential recoil ion energy spectrum. To obtain an integral recoil ion energy spectrum, the program verifies whether a particle with that certain energy can be detected. First of all the particle needs to be able to escape the decay trap; to this end the cut-off angle is taken into account. And secondly the recoil ion energy needs to be sufficiently high in order to pass the retardation potential; also the charge of the particle is taken into account for this. The code taking care of these two conditions is:

```
if(notTrapped(energy) && energy_after_traps/charge>(double)(j)*step)
spectrum++;
```

The function ‘notTrapped’ is shown in section C.3.2, ‘(j)*step’ is the retardation potential and the rest is self-explanatory. For example, to generate an integral recoil ion energy spectrum in retardation steps of 5 V and with 10^6 events in the first bin, 10^6 particles are generated for each retardation potential and for each particle it is verified whether it can be detected or not.

At that point there are two ways to proceed;

- An integral recoil ion energy spectrum for a specific value of a can be generated. This spectrum is then slightly modified, e.g. by shifting the energy bins, and then fitted with the analytical expression for an integral recoil ion energy spectrum. The influence on a from the disturbed spectrum is taken from the fit. This method is limited as the fit will only work in the case where the systematic effect mimics a change in a . This method will be referred to as the analytical method. Additionally, there is a small discrepancy between the simulated spectra and the analytical function; spectra simulated for $a = 0.9004$ will yield a result of $a = 0.8999(4)$ when fitted with the analytical function, which is off by $-0.15(3)\%$. This is caused by limitations of the numerical representation of the analytical function; i.e. rounding errors. These become significant due to the complexity of the numerical expression for this function.
- For other cases another method is used. Spectra are now generated for a specific value of a , with a disturbing effect, e.g. a deviating energy distribution. Two additional recoil ion energy spectra are then generated for $a = 1$ and $a = -1$, without the disturbing effect. The first spectrum is then fitted with a linear combination of the latter two spectra. This method is also the method that will be used for the data-analysis at WITCH. To fit a measured spectrum two spectra will be generated by the tracking simulations for extreme values of a , taking into account all known and measured systematic effects. If the systematic effects are under control this should yield a good fit of the measured spectrum and a determination of a . This method will be referred to as the simulation method.

C.3 Simulations

In this section the way each systematic effect was modelled in the simulations is documented. All spectra were generated for ^{35}Ar decay, with a Q -value of 5.9653 MeV, a recoil endpoint energy of 452.6 eV and $a = 0.9004$.

C.3.1 Analytical Method

For the investigation with the analytical method an initial spectrum was used with 10^6 particles in the first bin and a bin width of 1 V. The complete investigation with this method was thus based on one generated spectrum.

Energy Shift

A shift in energy is modelled by changing the energy of the bins. This was done for shifts from 0.0 V to 0.5 V. This effect can be compensated for by allowing the energy shift to be a parameter in the fit as well.

Ion Losses from Decay Trap

The ion losses from the decay trap are assumed to be constant in time; this does not have to be the case *a priori*. The first bin stayed unmodified and each consecutive bin was scaled with an increasing factor. For this an experimental cycle was assumed where the retardation voltages changes from 0 V to 500 V in 2.5 s.

```
// losses in the traps, with the assumption of 500 steps of 1eV,
// and 100V = 0.5s
double loss = 0.002; // loss per second, if started with 1,
                      // after 1s, the countrate will be
                      // reduced with 0.002
double loss_step = loss/200;
double reduction = 1;

for ( int i = 0; i < n ; i++ )
{
    x2[i] = x2[i]*reduction; // x2 is an array with the
                           // detected events per bin
    reduction = reduction - loss_step;
}
```

Wrong Assumption about Half-life

A deviation on the half-life is modelled as;

$$e^{-\ln(2) \cdot t / (t_{1/2} + \delta)} = e^{-\ln(2) \cdot t / t_{1/2}} \cdot e^{\ln(2) \cdot \frac{t}{t_{1/2}} \frac{1}{1 + t_{1/2}/\delta}} \quad (\text{C.6})$$

For the simulations the first factor of equation C.6 is set to unity as this will be taken into account in the data-analysis. Possible deviations from the half-life can not be taken into account; one has to rely on other, more accurate, measurements for a correct determination of the half-life. The same experimental cycle as with ion losses from the decay trap was assumed.

```
double hl_dev; //absolute half-life deviation
hl_dev = 0.001;

for ( int i = 0; i < n ; i++ )
{
    x2[i] = x2[i]*TMath::Exp(TMath::Log(2)*i/200/1.7752
                           *(-1/(1+1.7752/hl_dev)));
}
```

C.3.2 Simulation Method

For these simulations, a spectrum was generated for each situation.

Imprecision Power Supply

An imprecision of the power supply, not an inaccuracy, was modelled by changing the energy of the recoil ion randomly according to a Gaussian distribution where the standard deviation is the precision of the power supply. It was assumed that if a power supply has a precision of 1 V, for instance, each time the power supply is set to a certain value the actual value can deviate according to a Gaussian distribution with a standard deviation of 1 V. For the power supply of the retardation potential this is the same as assuming that the energy of the particle changes according to this distribution.

```
double SupplyDeviation(double energy)
{
    // PS_dev is the precision of the power supply
    if ( PS_dev == 0 ) return energy;
    double chance = mrand(); // mrand() returns a random number
                             // between 0 and 1
    double angle = 2*3.141592*mrnd();
    if ( cos(angle) >= 0 ) energy +=
        sqrt(-2*PS_dev*PS_dev*log(chance) );
    if ( cos(angle) < 0 ) energy -=
        sqrt(-2*PS_dev*PS_dev*log(chance) );

    if (energy < 0) energy = -energy;
    return energy;
}
```

Thermal Doppler Broadening

For this effect an initial energy for the recoil ion was generated according to a Maxwell-Boltzmann distribution. This initial energy was then combined with the recoil energy to get the final energy of the recoil ion.

```
double DopplerBroadening(double energy)
{
    // T is the mean temperature of the Maxwell-Boltzmann distr.
    if (T == 0) return energy;
    double doppler_energy;
    //generate velocity according to Maxwell-Boltzmann distr.
    double vmb = sqrt(-2.0*kb*T/M*log(1-sqrt(mrand())));
    vmb = vmb * vmb;
    vmb = vmb*M/2/e; //kinetic energy in eV;
    // add energies, depending on the angle between
    // recoil velocity and initial velocity
    doppler_energy = energy + vmb + 2*sqrt(energy*vmb)*(2*mrnd()-1);
    return doppler_energy;
}
```

Magnetic Field Ratio

The conversion of radial kinetic energy into axial kinetic energy was simulated for this. In the analysis $RM = 0.01666$ was the assumed value, where small deviations were allowed to this.

```
double MagneticFieldRatio(double energy)
{
    // RM is the magnetic field ratio, e.g. 0.1/6
    if (RM == 0 ) return energy;
    double chance = mrand();
    return ( energy*(1-4*RM*(chance-chance*chance)) );
    // the change of energy is
    //  $E ( 1 - \text{magnetic field ratio} * \sin^2 \theta )$ 
    //  $\theta$  is distributed according to  $\arccos(2x-1)$ 
    // with  $x$  between 0 and 1
    // this results in  $E ( 1 - 4 \text{ ratio } x ( x- 1 ) )$ 
}
```

Error on Endcap Potential

For this simulation endcap electrode voltages of 1 V were assumed. Different spectra were then generated according the code below for deviations in this voltage (V). The spectra are modified due to a different cut-off angle and thus a different fraction of ions that stay trapped after the decay.

```
bool notTrapped(double E)
{
    double chance = mrand(); // mrand is a random number
                             // between 0 and 1
    // charge is the charge of the particle
    // V is the depth of the decay trap
    // E is its recoil energy
    if(chance<=(1-sqrt(charge*V/E))){return true;}
    else return false;
}
```

Inhomogeneous Detection Efficiency

For this simulation an array with random numbers between 0 and 1 are generated. This array corresponds to the detector surface in areas of 1 mm^2 . The array was modified so that it gives inhomogeneities in the surface of detection centred around 100 %. The energy dependence of the focussing was modelled by a Gaussian distribution of the spot size on the detector with a standard deviation of $(E/200 + 0.75)/3$. This is loosely based on tracking simulations where recoil ions (from an ion cloud with a radius of 2 mm) with a maximum energy

of 50 eV reach the detector within a radius of 1 cm and those with 450 eV as maximum energy within 3 cm, with the retardation potential set to 0 V.

```
double DetectionEfficiency(double energy)
{
    double chance = mrand();
    double angle = 2*3.141592*mrnd();
    double st_dev = energy/200+0.75;
    double r,x,y;
    int x_int, y_int;

    r = sqrt(-2*log(chance) )*10*st_dev/3;
    if (r > 40) { return 0;}
    x = r*cos(angle);
    y = r*sin(angle);

    x_int = (int) (x + 40.5);
    y_int = (int) (y + 40.5);

    // det_surface is a 81x81 array with random values
    // between 0 and 1
    double eff = (2*det_surface[x_int][y_int]-1)*eff_scaling;

    eff = 100+eff;
    eff /= 100;
    return eff;
}
```

Ion Cloud Potential

To calculate the influence of the ion cloud potential, first the Coulomb potential generated by 10^6 ions was estimated. This distribution was approximated by

$$\text{potential} = Q_{\text{scaling}} / (0.6665 * \text{position} + 0.1469);$$

with ‘position’ the distance from the centre of the trap. ‘Qscaling’ is a scaling factor for the number of ions. The ions’ position distribution was assumed to have a standard deviation of $\sqrt{2}$ mm radially and $\sqrt{7}$ mm axially, which is slightly reduced by the cosine factor.

```
double IonCloudOffset(double energy)
{
    double radius, z, position, potential;
    double chance = mrand();
    double chance2 = mrand();
    double angle = mrand()*2*3.141592;
    double angle2 = mrand()*2*3.141592;
```

```
radius = sqrt(-2*2*log(chance) )*cos(angle);
z = sqrt(-2*7*log(chance2) )*cos(angle2);

position = sqrt(radius*radius+z*z);

potential = Qscaling /(0.6665*position+0.1469);
if (potential > 0.576138626*Qscaling)
    potential = 0.576138626*Qscaling;

return (energy + potential);
}
```

Appendix D

Additional Articles

Two articles are included in this appendix:

- The WITCH experiment: Acquiring the first recoil ion spectrum [Kozlov et al., 2008],
- First detection and energy measurement of recoil ions following β decay in a Penning trap with the WITCH experiment [Beck et al., 2011].

They are included here as they form an integral part of this work. They are, however, not included in the main body of this work as the description of the setup in those articles has been superseded already by upgrades installed during the period of this PhD work; e.g. the issue of ionisation processes and the quick charge exchange of ^{35}Ar mentioned in [Beck et al., 2011] have both been solved. The first article describes in detail how the data-acquisition at WITCH was realised during the ^{124}In run of 2006. At present, the same data-acquisition system is still in use. The second article investigates in detail what can be learnt from the data obtained in the ^{124}In run of 2006.

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The WITCH experiment: Acquiring the first recoil ion spectrum

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Abstract

The standard model of the electroweak interaction describes β -decay in the well-known V–A form. Nevertheless, the most general Hamiltonian of a β -decay includes also other possible interaction types, e.g. scalar (S) and tensor (T) contributions, which are not fully ruled out yet experimentally. The WITCH experiment aims to study a possible admixture of these exotic interaction types in nuclear β -decay by a precise measurement of the shape of the recoil ion energy spectrum. The experimental set-up couples a double Penning trap system and a retardation spectrometer. The set-up is installed in ISOLDE/CERN and was recently shown to be fully operational. The current status of the experiment is presented together with the data acquired during the 2006 campaign, showing the first recoil ion energy spectrum obtained. The data taking procedure and corresponding data acquisition system are described in more detail. Several further technical improvements are briefly reviewed.

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1. Introduction

The weak interaction described by the Standard Model has the well-known V (vector)–A (axial-vector) structure. The most general Hamiltonian for nuclear β -decay, however, suggests more possibilities consistent with Lorentz-invariance [1,2]: scalar (S), tensor (T) and pseudoscalar (P) interactions. The presence of S- and T- contributions in weak interaction is not yet fully ruled out experimentally, i.e. the present constraints are at the level of about 8% (95% C.L.) of the V- and A-interaction [3]. One of the probes to search for these exotic interactions is to study the β - ν angular correlation. This correlation for unpolar-

ized nuclei can be characterized by the β - ν angular correlation coefficient a the value of which depends on the type of interaction involved and is for instance for pure Fermi transitions given by

$$a_F = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}. \quad (1)$$

From the properties of interactions it can be shown that this coefficient a also determines the shape of the recoil ion energy spectrum [4]. The primary goal of the WITCH experiment is to measure this recoil ion energy spectrum with high enough precision in order to infer new constraints on the S- or T-contributions. The issue of exotic scalar and tensor interactions was recently addressed in a number of experiments in nuclear physics [5–9] as well as particle physics (for example [10]). One should also note

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here that the presence of these interaction types implies the existence of corresponding mediator bosons. An extensive review can be found in [3,11].

2. Experiment

The WITCH set-up is installed at ISOLDE/CERN [12], thus fulfilling the requirement of the experiment for a high intensity radioactive source. The quasi-continuous beam produced at ISOLDE is first trapped and bunched by the REXTRAP facility [13]. The ion bunch ejected from REXTRAP is then guided into the WITCH set-up. The principle of the set-up is based on a combination of a double Penning trap system to form a scattering-free source and a retardation spectrometer (MAC-E filter) to measure the energy of the recoil daughter ions (Fig. 1). This combination was chosen to obtain high accuracy in measuring recoil spectra with the end point energy of the order of 100 eV. First, the ions are decelerated with a pulsed drift tube [14] in order to be loaded into the first Penning trap, called cooler trap. There they are cooled by buffer gas collisions and mass selectively purified. The ion cloud is then transferred into the second Penning trap, the decay trap. The energy of the ions leaving the decay trap after β -decay is probed by an electrostatic retardation potential. Both traps are placed in a 9 T magnetic field while the retardation analysis plane is at 0.1 T field. According to the working principle of the retardation spectrometer this leads to a 98.9% conversion of the radial energy into axial energy at the analysis plane. The ions of charge state q that pass the retardation potential are accelerated to qU keV, with $U \sim 10$ kV, and focused towards a position sensitive micro-channel plate detector (MCP). Position sensitivity is realized by delay line anodes, i.e. the one-dimensional position of the particle hit is deduced from the difference of the propagation times to both ends of the corresponding wire [15]. Varying the retardation potential over the neces-

Table 1
Estimate of the presently best achieved total efficiency in comparison with the values for the ideal set-up (for parameters that were not yet studied the values of an ideal set-up are taken to calculate the total efficiency)

Description	Ideal set-up (%)	Best achieved 2004–2006 (%)
Beamline transfer + pulse down	50	~80
Injection into B-field	100	~20
Cooler trap efficiency	100	~50
Transfer between traps	100	~70
Storage in the decay trap	100	100
Fraction of ions leaving the decay trap	~40	Not studied
Shake-off for charge state $n = 1$	~10	Not studied
Transmission through the spectrometer	100	100 (prelim.)
MCP efficiency	60	52.3(3) [15]
Total efficiency	~1	~0.12

sary range allows to measure the full integral recoil ion spectrum. A more detailed description of the WITCH experiment can be found in [4,16].

3. Current status

The main effort during the year 2006 was to improve the overall efficiency of the set-up [14,17] including optimization of REXTRAP for the needs of the WITCH experiment and to extend the data acquisition (DAQ) system to control more of the important parameters (Section 5). An overview of the present efficiencies is given in Table 1. There is good improvement in relation to year 2004 [16] but one order of magnitude is still missing in comparison with the ideal set-up, mainly due to a not yet fully optimized injection into the magnetic field. Another recent achievement is the mass resolving power of the cooler trap $m/\Delta m \sim 1\text{--}2 \times 10^5$, thanks to newly produced traps that were silver- and gold-plated in GSI (Germany).

While improving the efficiency of the set-up several new problems showed up as well. The major ones are the discharges in the cooler trap and in the spectrometer, related to the buffer gas pressure and γ -activity present in the system, and a sparking of the acceleration part for voltages above 7 kV. This limited the functionality of the system but did not prevent us from measuring the first recoil ion spectrum.

4. First recoil ion spectrum

To perform a proof-of-principle experiment a high beam intensity is required. Moreover, one can switch to a beta-minus isotope in which case all recoil daughter ions have a non-zero charge contrary to the beta-plus case where one has to rely on the shake-off probability to obtain 1+ ions because of the 1+ charge state of the incoming mother ions. In this way one can compensate for the missing order of magnitude in the overall set-up efficiency (Table 1). Thus, ^{124}In was chosen for the proof-of-principle experiment. A drawback of this isotope is the complicated decay

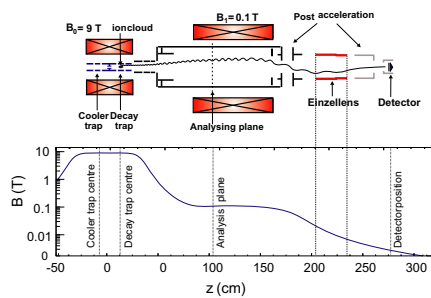


Fig. 1. Principle of the WITCH experiment: the retardation spectrometer is shown together with the corresponding magnetic field profile. $z = 0$ corresponds to the center of the 9 T magnet. The positions of the traps, the analysis plane and the recoil ion detector are indicated.

scheme, with a significant amount of γ 's, and that the incoming beam from ISOLDE contains both ground state ^{124g}In and isomer ^{124m}In . The end point energy of the ^{124g}In and ^{124m}In recoil ions from β -decay is different, being 196 eV and 83 eV respectively. In addition, the recoil ion spectra of both states are influenced by the γ -radiation which follows the β -decay. This fact has to be correctly taken into account in the analysis [18]. The discharge problem in the spectrometer mentioned above did not allow to measure the recoil energy spectrum by using the retardation spectrometer. The Einzellens electrode (Fig. 1) was used instead. Discharges in the cooler trap were avoided by using a lower buffer gas pressure. First, to verify that recoil ions are indeed present in the system a simple Off/On cycle was executed, i.e. switching between no retardation and full retardation of the recoil ions. The expected significant drop in a count rate when the full retardation is applied was observed. Then the measurement cycle was changed to 23 retardation steps going up from 0 V to 220 V and the first recoil ion spectrum was obtained (Fig. 2). The data presented were acquired during ~ 50 min. To verify that the measured spectrum originates from the recoil ions of ^{124}In and is not caused by any correlated background, two off-line sources (a β -source of ^{90}Sr and a γ -source of ^{60}Co) were later installed for two independent measurements. The spectra measured under the same circumstances as during the on-line experiment are presented in Fig. 3 showing no similarity to Fig. 2. The data taken with the ^{90}Sr source together with GEANT4 simulations [16] allow to estimate the β -background present during the on-line experiment. The fluctuation of data points taken with the ^{60}Co source being larger than the statistical uncertainty suggests that certain discharges due to the γ -activity could still have been present. The detailed analysis of the measured ^{124}In recoil spectrum is given in [18].

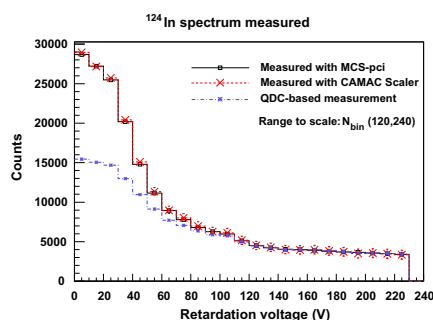


Fig. 2. First recoil ion spectrum measured. The incoming beam is a mixture of ^{124g}In and ^{124m}In ; 23 retardation steps in the range of 0–220 V. Three spectra shown correspond to different methods of data acquisition (see Section 5).

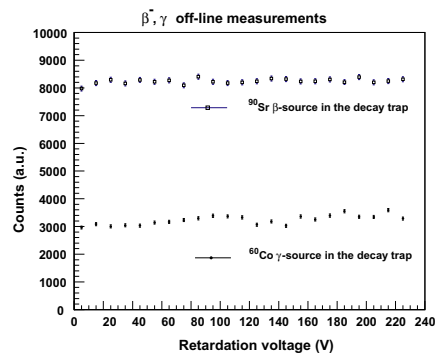


Fig. 3. Off-line measurements with the β -source (^{90}Sr) (top) and γ -source (^{60}Co) (bottom) in the decay trap. Absolute intensities are not to be compared due to different sources strength and measurement time. The running cycle was exactly the same as during the on-line measurement of ^{124}In .

5. Data acquisition

Two approaches are available for the recoil ion spectrum measurement: (1) fix the retardation value for each trap filling and (2) scan all retardation voltages during one trap filling. The first one is not directly possible at the moment since a normalization between different trap loads is necessary in this case (this is currently being developed, see Section 6) while the latter one requires that the half-life of the isotope is taken into account in the analysis. During the ^{124}In measurement the second option was chosen, thus the recoil spectra in Fig. 2 are not corrected for the half-lives of ^{124g}In (3.11(10) s) and ^{124m}In (3.7(2) s).

It is obvious that storing of more parameters during the measurement allows a better check of different systematic effects. However, it can also introduce a significant dead time of the acquisition system. Therefore, a two branch DAQ system was developed for WITCH (Fig. 4). The first branch (Fig. 4(a)) performs a simple counting and uses an ORTEC[®] multi-channel scaler PC card (MCS-pci) with provided software. This card records the number of events as a function of time, accepts counting rates up to 150 MHz and allows to specify a timing channel from 100 ns to 1300 s. These characteristics perfectly satisfy the WITCH requirements of ~ 0.1 MHz count rate and a few seconds data acquisition cycle. Another highly important parameter is zero dead time between timing channels and at the end of the cycle. When the card advances from one time bin to another a “Channel Advanced” TTL-signal is generated which is then used to drive the retardation supply to change to the next retardation step. A direct connection between the time channels and the retardation steps is thus provided. For instance, during the ^{124}In measurement

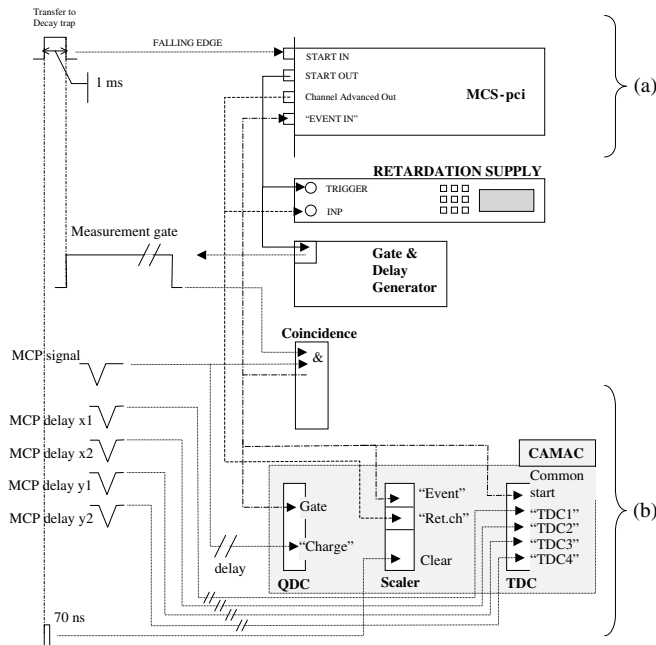


Fig. 4. DAQ principle scheme of the WITCH experiment. Two branches of the system are indicated: (a) fast counting, based on the ORTEC MCS-pci card and (b) event-by-event, based on the CAMAC system.

one retardation channel corresponded to a time bin of 100 ms within one trap load. The data acquired are displayed on-line by ORTEC[®] software while they are saved to a hard-disk after 10 cycles. The second branch (called “event-by-event”, Fig. 4(b)) is based on a CAMAC system and LabVIEW software and stores an additional information for every event: four delay times to reconstruct the position of the event on the MCP detector, the charge collected by the MCP, the current retardation step and the total number of events collected since the beginning of the DAQ cycle. The charge information is important because the charge distribution, or pulse-height distribution (PHD), differs for ions and β 's. For instance, comparing PHDs for the first retardation steps and for the last (stepping goes up from 0 V to 220 V) one can see (Fig. 5) that in the beginning of the retardation this distribution has a Gaussian-like part which is typical for ions while at the end it is more exponential-like, typical for β 's. This provides additional proof that the main signal measured corresponds to ^{124}In ions. Moreover, by combining the charge information with the position of an event one can select the outer rim of the detector and check that the events reg-

istered there have the PHD typical for β 's and not for ions [18], thus confirming that the ion signal was well within the detector for all retardation steps and avoiding possible systematic effects on the spectrum. The total number of events since the beginning of the cycle and the current retardation step are recorded by a 100 MHz CAMAC scaler to have a reference with the first branch of the DAQ. The read-out of the second branch is triggered by an event in the QDC module (charge to digital converter). When the CAMAC system is read the QDC and TDC (time to digital converter) modules are emptied but not the CAMAC scaler that is cleared only at the beginning of the next cycle (Fig. 4). From the information recorded one can reconstruct the measured spectrum in three ways: (1) directly from the data acquired with the first branch (MCS-pci card), (2) using the data collected in the CAMAC scaler and (3) counting how often the QDC module was triggered for every retardation step. As can be seen from Fig. 2 the first and second methods correspond pretty well to each other while method (3) misses a significant portion of the counts at high count rate. By comparing the data of the 2nd and 3d methods one can deduce the dead time of

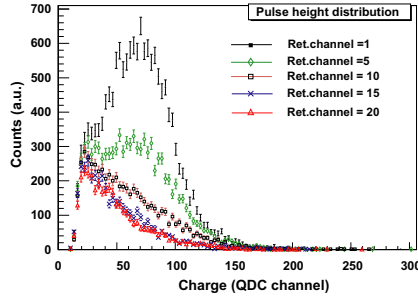


Fig. 5. Pulse-height distributions for different retardation steps.

the second branch of the DAQ (Fig. 6). The average value for two data sets is $\tau_{\text{dead time}} = 346.6 \pm 2.0 \mu\text{s}$. Thus the “event-by-event” DAQ provides very important information to check a number of systematic effects but has a significant dead time, such that the recoil ion spectrum has to be fitted on the basis of the data collected with the first branch of the DAQ.

The usual measurement cycle starts when the ions are transferred into the decay trap. Therefore, the transfer signal triggers the whole data acquisition (Fig. 4). The falling edge of the transfer TTL-signal gives the start for the MCS-pci card. The width of the time channel and the number of channels are specified via the software. This number of time bins has to correspond to the number of voltage steps of the retardation supply. The start of the MCS-pci card is used to generate a “measurement window” to avoid further counting after the decay trap is emptied. This start signal also triggers the retardation supply so that it becomes ready for stepping. The change of the retardation step is driven by the change of the time channel in the MCS-pci card. The signal from the rear face of the MCP is amplified, delayed and sent to the QDC for the charge measurement

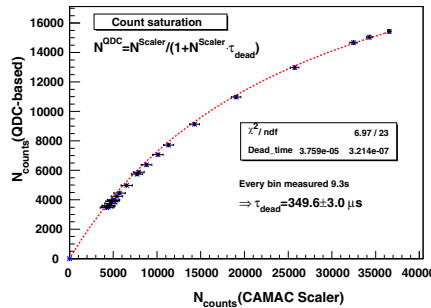


Fig. 6. Saturation of the count rate in the QDC-triggered system.

but it is also discriminated and put in coincidence with the “measurement window”. The NIM logic signal after the coincidence unit is then used as a QDC gate and to give a “Common start” for the TDC. This NIM signal is also sent for counting to the “Event In” input of the MCS-pci card and to the CAMAC scaler. The four signals from the delay lines of the MCP are amplified, discriminated and then sent to the stop inputs of the TDC. The whole cycle can be as well adopted for other measurement scenarios, for instance for the Off/On sequence mentioned above (Section 4).

6. Outlook

There is still room for further developments. Here we mention several issues. The discharge problems definitively have to be investigated in more detail. Section 5 clearly suggests that the “event-by-event” branch has to be improved in order to reduce the dead time. One of the possibilities is to use a flash ADC or fast digitizer to record the whole shape of the MCP signal and then use a software routine to analyze it. However, this will significantly increase the amount of data to be stored. The already existing “event-by-event” system may require up to ~ 50 Gbyte/day. Another fast available solution is to use the existing ISO-LDE DAQ system based on VME electronics and MBS software, the standard DAQ software at GSI (Germany). This system is not yet the ideal solution but it should give one order of magnitude reduction of dead time. Another ongoing development is related to a scintillator β -detector to be installed in the decay trap [19]. This will allow to have a normalization between different trap loads, to perform TOF measurements, etc. The first prototype was produced in Prague and it is currently being tested in Leuven. One can also improve the DAQ cycle such that the retardation steps close to the end point of the spectrum, i.e. with less statistics, are measured longer. A last idea, but not least is to perform a case study for an energy sensitive detector instead of the currently used MCP. Ideally this will allow to separate the different charge states of the recoil ions and to distinguish ions from β 's by their energy. The key issue in this separation is that the ions of different charges have different energies due to the electrostatic re-acceleration (i.e. $E_{\text{ion}} = q \cdot U_{\text{acc}}$). With $U_{\text{acc}} > 30$ kV the ions may have enough energy, for instance to pass the dead layer of solid state detector and leave sufficient ionization signal [20]. This ion signal should as well be different from the signal left by β 's with typical energies of the order of 1 MeV.

7. Conclusion

The WITCH experiment opens new possibilities for recoil ion spectrometry with the primary goal to test the Standard Model for the presence of scalar and tensor exotic interactions. Recently the proof-of-principle experiment was successfully completed and the first recoil ion spectrum was obtained. Details of the measurement procedure with

emphasis on the current version of DAQ system were presented. Also several checks of the validity of the data obtained were described. Further developments, in order to improve the functionality of the experiment, were briefly discussed as well.

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First detection and energy measurement of recoil ions following beta decay in a Penning trap with the WITCH experiment

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Abstract. The WITCH experiment (Weak Interaction Trap for CHarged particles) will search for exotic interactions by investigating the β - ν angular correlation via the measurement of the recoil energy spectrum after β -decay. As a first step the recoil ions from the β^- -decay of ^{124}In stored in a Penning trap have been detected. The evidence for the detection of recoil ions is shown and the properties of the ion cloud that forms the radioactive source for the experiment in the Penning trap are presented.

1 Introduction

In the standard model description of the weak interaction only two out of ten theoretically possible terms are included in the $V - A$ Hamiltonian of the four-fermion contact interaction that describes low-energy processes like β -decay [1]. Although this still provides a good description of the experimental data to date, scalar- or tensor-type currents, which are absent in the standard model, have not fully been excluded [1]. To determine the contributions of the various possible terms in the Hamiltonian, correlation coefficients in β -decay are often measured (see *e.g.* [2–14]). The β - ν angular-correlation coefficient, a , has been addressed several times in the past because of its high sensitivity to these exotic weak currents [15–26]. Since measuring the correlation between the directions of emission of the β -particle and the neutrino by directly observing the neutrino is virtually impossible, a is commonly inferred from a measurement in which the recoiling nucleus is observed. The WITCH experiment [20] was set up at ISOLDE/CERN to measure the recoil ions after β -decay and to determine the β - ν angular correlation from the spectral shape of their energy spectrum.

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2 Experimental set-up

Most of the recent β - ν correlation experiments observe the β -particle and the recoil nucleus in coincidence (see *e.g.* [17,18,23,24]). At the WITCH experiment, the β - ν angular-correlation coefficient a will be derived from the shape of the recoil energy spectrum alone. This can be done with high statistics using different isotopes independent of their chemical properties. The most significant limitation at WITCH stems from the complexity of the decay of the chosen isotope and therefore the ease with which the recoil energy spectrum can be interpreted [20]. Due to the possibility to measure the recoil spectra from the decays of several different isotopes, systematic effects and potential experimental artefacts can be studied in detail. The initial goal is to reach a sensitivity of $\Delta a < 0.5\%$, comparable with the best individual existing experiments. However, as the typical nuclear recoil energies after β -decay are only of the order of 100 eV, inelastic scattering of the recoiling particles in the source is of concern. In order to avoid the latter, the radioactive ions are stored in a Penning trap [27]. For the measurement of the recoil energy spectrum WITCH uses an electromagnetic retardation spectrometer with magnetic adiabatic collimation [28,29]. An overview of the set-up is shown in fig. 1. The radioactive ions obtained from ISOLDE, CERN [30] are first bunched and cooled in the REXTRAP cooler and buncher Penning trap [31]. They are passed on to the WITCH experiment where they are first decelerated from an energy of 30 keV

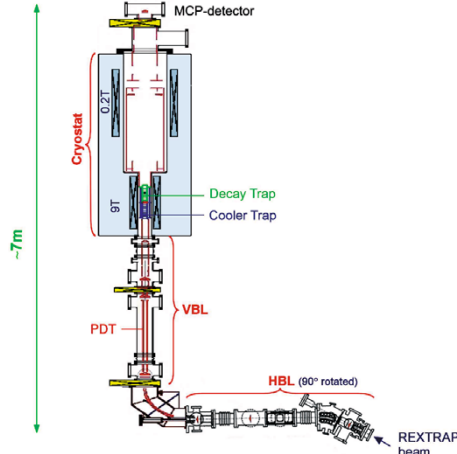


Fig. 1. Schematic overview of the WITCH set-up and its environment. Radioactive ions received from ISOLDE are cooled and bunched in REXTRAP, sent into the WITCH horizontal beamline (labeled HBL), decelerated in the vertical beamline (labeled VBL) containing the pulsed drift tube (labeled PDT) and injected into a first Penning trap. After cooling in this cooler trap they are transferred to a second Penning trap where the stored ion cloud serves as the source for the experiment. The energy of recoil ions from decays in this ion cloud is probed by a retardation potential. Recoil ions with sufficient axial energy to pass the retarding potential are accelerated and counted with an MCP detector. For more details see ref. [20].

to several 100 eV by means of a pulsed drift tube [32]. The decelerated ions are injected into the first of two Penning ion traps in a magnetic field of 9 T, the cooler trap of WITCH. In this trap the ion cloud is cooled by the helium buffer gas and mass selectively purified [33, 34]. The ions are then transferred to the second Penning trap, the decay trap, in which they are held either until they decay or until the trap is emptied for a subsequent measurement cycle. The trap is emptied by ejecting the stored ions backward towards the vertical beamline. At the same instant the retardation voltage is lowered to zero in order to remove any ions or electrons stored in the spectrometer, which could cause additional background.

The decay trap is separated from the cooler trap by a differential pumping barrier to reduce scattering in the source due to the buffer gas. During the measurements presented in the following the pressure in the decay trap was of the order of 10^{-6} mbar of helium leaking through from the cooler trap as estimated from gas flow calculations. The helium is also the dominant residual gas in the spectrometer leading to a pressure of $\approx 5 \cdot 10^{-8}$ mbar. Both pressures are sufficiently low to strongly suppress the scattering of recoil ions in the decay trap and the spectrom-

ter. They are within the design parameters of WITCH [20] but can still be improved. During the measurements the decay trap was operated at a depth of ≈ 8 V. The recoil ions are emitted isotropically in the decay trap and in general have a maximum kinetic energy of $\mathcal{O}(100$ eV). Those recoil ions from β -decay with an axial energy that is larger than the depth of the decay trap will leave the trap and move from the high magnetic field of 9 T in the decay trap into the weak magnetic field of 0.1 T at the analysis plane where an electric retarding potential U_{ret} is applied. Due to the magnetic gradient force most of the energy of the particles is in the longitudinal component once they reach the weak field region and thus can be probed there by the retardation potential. This is the principle of a MAC-E filter (electrostatic spectrometer with magnetic adiabatic collimation [28, 29]), which *inter alia* is used at experiments to determine the neutrino mass by observing the β -decay of tritium [35, 36]. All ions that cross the retardation barrier are detected with a 47 mm diameter position-sensitive microchannel plate detector [37, 38]. To achieve a good detection efficiency the ions are accelerated with up to -10 kV between the analysis plane and the detector. An Einzel lens focusses the accelerated ions onto the detector. By varying the retardation potential U_{ret} an integral energy spectrum of the recoil ions is obtained.

3 Test case: ^{124}In

In the past few years the WITCH set-up has been extensively tested and optimized [39, 40]. In order to test the operation of WITCH and to measure a first recoil energy spectrum, an isotope which decays via beta-minus decay and which has a low ionization potential, ^{124}In , was chosen. Indium has a very low ionization potential ($\Phi_{\text{In}} = 5.8 \text{ eV}^1$), which prevents losses from the decay trap caused by charge exchange with the residual gas ($\Phi_{\text{He}} = 24.6 \text{ eV}$, $\Phi_{\text{N}_2} = 15.6 \text{ eV}$, $\Phi_{\text{O}_2} = 12.1 \text{ eV}$). The Q -value of the β^- -decay of ^{124}In is 7360 keV. The highest recoil energy of $E_{rec} = 196 \text{ eV}$ stems from decays to the first excited state at 1131.6 keV, since no decay occurs to the ground state. This excited state decays within less than 1 ps to the ground state. The recoil due to the emitted γ -particle increases the maximum recoil energy to $E_{max} = 267 \text{ eV}$. As a complication, ^{124}In has an isomer, ^{124m}In , with an excitation energy of 50 keV. The β^- -decay with the highest Q -value also occurs to excited states only, with the lowest state at 4838 keV. This results in a maximum recoil energy of 123 eV. When the γ recoil is taken into account, it is increased to 268 eV. The half-lives of the two indium isomers are $t_{1/2}(^{124m}\text{In}) = 3.7 \pm 0.2 \text{ s}$ and $t_{1/2}(^{124}\text{In}) = 3.11 \pm 0.10 \text{ s}$. ^{124}In is produced in large amounts at ISOLDE ($> 10^8$ ions/s). Thus, potentially still low efficiencies at WITCH do not pose a problem.

β^- -decay of the singly charged ^{124}In ions offers an additional advantage over β^+ -decay due to electron shake-off: after the β^- -decay of neutral atoms typically about

¹ All ionization potentials are taken from [41].

10% of the daughter ions will be accompanied by one shake-off electron due to the sudden change in the electrical potential that the orbital electrons experience, caused by the change in the nuclear charge due to the β -decay (see *e.g.* [42]). For the following discussions it is assumed that this is also the case for the decay of singly charged ions. It follows that the singly charged ions stored in the decay trap will lead to predominantly doubly charged positive recoil ions and thus offers a count rate higher by an order of magnitude in comparison to beta-plus decay. For the latter the daughters of the decay of singly charged ions will be neutral and one has to rely on shake-off to get charged recoil ions. The electron shake-off after β -decay at WITCH will be investigated in detail in the future.

Both indium isomers have a complex decay scheme and produce a high γ -ray background, which caused discharges in the combined electric and magnetic fields of the spectrometer and the acceleration section. Therefore, the acceleration and focussing electrodes had to be operated at voltages significantly below their design values, -4 kV and -7 kV instead of -10 kV, leading to some transmission losses of the ions. As another consequence, the retardation spectrometer could not be used as intended due to discharges at the main spectrometer electrode. Instead, the Einzel lens behind the main spectrometer electrodes, which is normally only used to focus the ions onto the detector, was used as a temporary retardation electrode. Both changes with respect to the design parameters of WITCH were acceptable for a first measurement of recoil ions but naturally prevented a precise measurement of their energy spectrum. Off-line measurements after the indium measurement with a γ -ray source (^{60}Co) at the place of the ion cloud confirmed that these discharges were indeed due to a high γ background [40] and therefore are expected to be absent with an isotope with lower γ multiplicity.

For the first measurement of recoil ions the Penning traps were operated in a magnetic field of $B_{\text{trap}} = 6$ T with a depth of $U_{\text{trap}} \approx 8$ V. The magnetic field in the analysis plane was $B = 0.1$ T, resulting in a field in the center of the Einzel lens that was used as temporary retardation electrode of $B_{\text{Einzel}} \approx 0.01$ T.

4 Results

4.1 Recoil ions from β -decay in the decay trap

The first measurement performed was an *on-off* measurement for which the retardation voltage was switched between two extreme values: $U_{\text{ret}} = 0$ V (*off*), letting all recoil ions pass, and $U_{\text{ret}} = 200$ V (*on*), by far large enough to retard all recoil ions from the β^- -decay of singly charged ^{124}In , which are at least doubly charged. A significant decrease of the count rate at the moment of the switching from *off* to *on* then indicates the presence of low-energy positive ions coming from the source. The measured count rate throughout this measurement cycle is shown at the top of fig. 2. The cycle starts when the ions are injected into the cooler trap. After 1.5 s they are

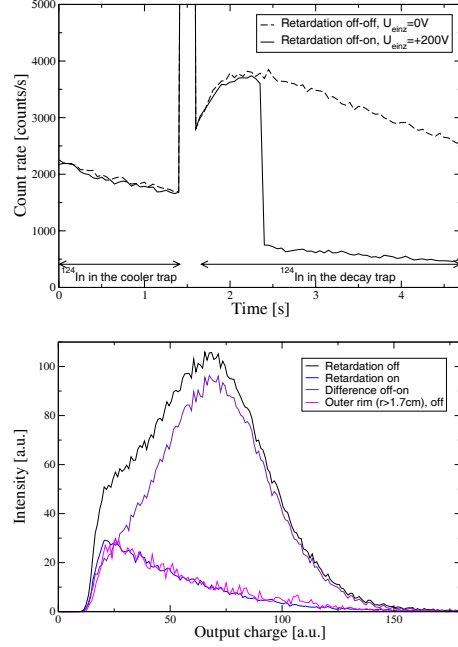


Fig. 2. Top: count rate throughout the measurement cycle during an *off-on* measurement. For the case *off-on* the retardation was switched *on* at time $t = 2.4$ s, leading to a clear drop in count rate as the recoil ions are being reflected by the retardation potential (see text for details). Bottom: pulse height distributions (PHD) obtained from the MCP detector during an *off-on* measurement (see also fig. 3).

transferred to the decay trap. Note that some ions were not captured in the decay trap and ended up on the detector, explaining the momentary increase in count rate at 1.5 s. In the *off-on* mode the retardation was switched on after 2.4 s. The curve marked *off-off* in fig. 2 shows the count rate for the mode where the retardation potential was not switched but otherwise used the same measurement cycle. As expected, switching the retardation voltage U_{ret} *on* results in a much lower count rate. The difference is attributed to ions with $E/q < U_{\text{ret}} = 200$ V and a signal to noise ratio of about 4:1. The *off-off* measurement was derived from 60 trap loads and the *off-on* measurement from 90 trap loads. Each had 95 time steps with 50 ms per step. The ions that hit the detector at 1.5 s caused a significant dead time of the detector during almost a second as can be seen from the variation of the count rate between 1.6 s and 2.4 s after the start of the measurement cycle in fig. 2 (top); see also [38] for more details.

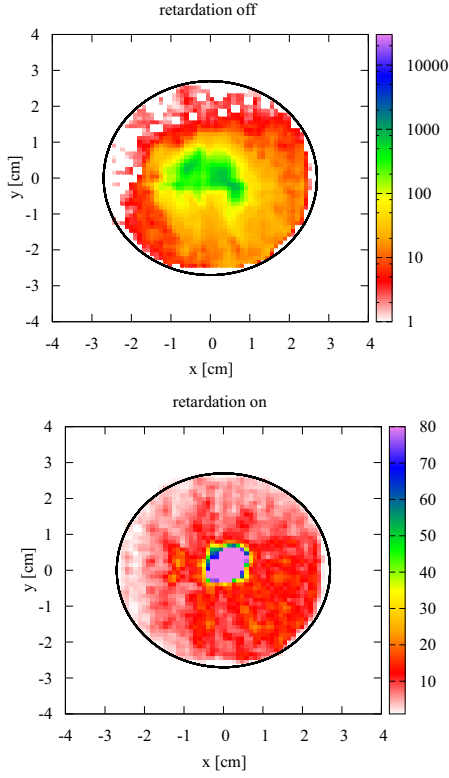


Fig. 3. Measured position distribution on the detector for retardation *off* ($U_{ret} = 0$ V, top) and retardation *on* ($U_{ret} = 200$ V, bottom). The *off* distribution shows both ions and β -particles, the *on* distribution β -particles only, except for the center where decays of ions were measured that were deposited on the detector during the loading of the decay trap due to non-optimal trapping efficiencies. The black circle denotes the extent of the detector with diameter 47 mm. Figure 4 shows the simulated position distribution for comparison.

The pulse heights obtained from the detector during both measurement periods are shown at the bottom of fig. 2. The exponentially decreasing pulse height distribution (PHD) observed during the retardation *on* period ($U_{ret} = 200$ V) is consistent with the PHD caused by β -particles as observed in off-line tests. The additional bell-shaped distribution during the retardation *off* period ($U_{ret} = 0$ V) is consistent with the PHD of ions on microchannel plates [37].

Besides the PHDs also the spatial distribution of the events on the detector was measured (fig. 3). They can

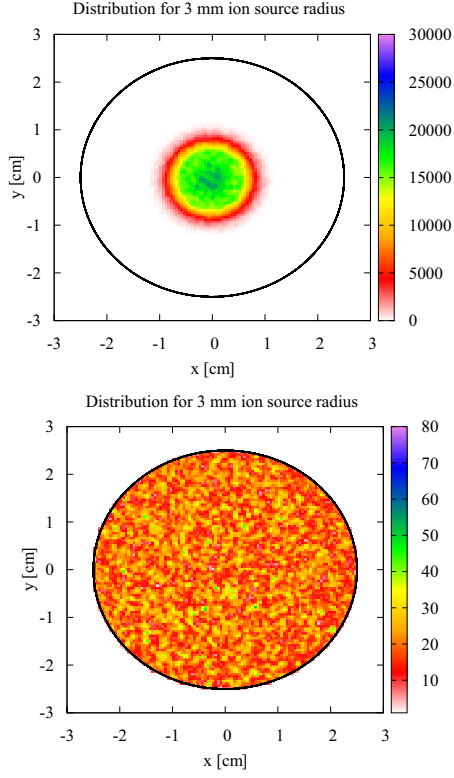


Fig. 4. Simulated position distribution of recoil ions (top) and β -particles (bottom) from the decay trap on the detector. In contrast to fig. 3 (top) the simulated distribution of the recoil ions does not include β -particles. The black circle denotes the extent of the detector.

be compared with those from microscopic tracking simulations of recoil ions and β particles from a cylindrical ion cloud in the decay trap with constant density to the detector (fig. 4). The simulations were performed for an ion cloud radius of 3 mm, for ions of charge state $q = 2^+$ and spectra corresponding to $a = -1/3$ using the maximum endpoint energies. The electrode potentials used in the simulations were those applied during the measurements. The measured position distribution shows a pronounced peak at the center of the detector when both the ion and the β -particle components are visible during the *off* measurement ($U_{ret} = 0$ V, fig. 3, top). In contrast, only a flat component with a narrow peak remains when the retardation is switched *on* ($U_{ret} = 200$ V) and no ions from the β -decay of the ^{124}In in the decay trap reach the de-

tector (fig. 3, bottom). The pronounced wide peak with retardation *off* can be described by the focussing of recoil ions from the trap onto the detector (fig. 4, top). The narrow peak for retardation *on* is due to radioactive ions that were shot onto the detector upon transfer and their decay on the MCP surface. The flat background across the full detector can in both cases be attributed to β -particles from decays in the decay trap (fig. 4, bottom). This is confirmed by the pulse height distribution of the events in the outer rim ($r > 1.7$ cm) of the detector in fig. 2 (bottom panel), which has exactly the same exponential shape as the pulse height distribution for the events observed with the retardation *on* ($U_{ret} = 200$ V) when only β -particles can reach the detector.

A fit of the half-life (see table 1) of the exponential decrease of the count rate, when the radioactive ions are inside the decay trap and the retardation is *off*, shows that the half-life is consistent with that of a mixture of ^{124}In and ^{124m}In and that, except for the radioactive decay, no significant loss of ions occurs during the 2.4 s measurement period.

In summary, the difference of the observed count rates for the retardation potential *on* and *off* shows that low-energy positively charged particles are detected. Their PHD shows that these particles are ions. The position distribution, especially in conjunction with the tracking simulations, further shows that these ions are consistent with ions from the decay trap. Together with the analysis of the half-life, this confirms that these are recoil ions from the β -decay of $^{124g,m}\text{In}$ in the decay trap, which are accompanied by a diffuse background of β -particles.

4.2 First recoil ion energy spectrum with WITCH

In order to obtain a first recoil energy spectrum with WITCH, the retardation potential was scanned in 23 steps during each trap load with a step size of 10 V and a step duration of 100 ms (fig. 5). This measurement cycle implicitly takes care of the normalization, provided that there are no losses of ions from the decay trap. As a consequence, in the analysis any such measured spectrum has to be corrected for the half-life due to the decay during the measurement: $N(U_{ret}) = N(t)/e^{-\lambda t}$ with $N(U_{ret})$ being the recoil spectrum, $N(t)$ the number of counts measured at time t and λ the decay constant of the radioactive decay. Such a measurement cycle also implies that the abscissa in fig. 5 corresponds to time as well as retardation potential, with $t = 0$ s corresponding to $U_{ret} = 0$ V.

Since the singly charged ^{124g}In and ^{124m}In ions decay via β^- -decay, the recoil ions are at least doubly charged ($q_{min} = 2$). Therefore, without any additional energy broadening, a retardation potential of $U_{ret} = E_{max}/q_{min} = 98$ V is sufficient to retard all recoil ions and constitutes the theoretical endpoint of the recoil energy spectrum (as indicated in fig. 5). In this case all events measured above this voltage are background due to β -particles from the β -decay. In practice, both Doppler broadening due to γ -decay in flight and thermal Doppler broadening due to a non-vanishing kinetic energy of the

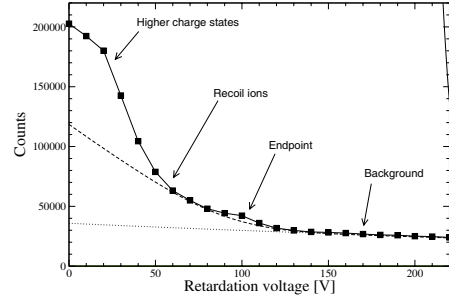


Fig. 5. Measured integral energy spectrum for the recoiling ions from the β -decay of $^{124g,m}\text{In}$. The spectrum consists of the sum of 500 trap loads, i.e. each data point has an effective measurement time of 50 s. The raw data are shown, i.e. the exponential decay has not been unfolded (squares). The data points are connected by a line to guide the eye. For comparison, a calculated recoil energy spectrum is shown for the lowest expected charge state $q_{min} = +2$ and for the maximal Q -value possible (dashed line). The constant background, which in this representation decreases with the decay constant of the ^{124}In decay, is also shown (dotted line).

radioactive ions in the decay trap will result in some events above the theoretical endpoint energy, as is visible in fig. 5. The γ -ray broadening will lead to an endpoint of $E_{max,\gamma} = 267$ eV and $U_{ret,\gamma} = E_{max,\gamma}/q_{min} = 134$ V. The calculation (dashed line) in fig. 5 includes the exponential decay, a Gaussian broadening to approximate the thermal Doppler broadening due to high kinetic energies of the decaying parent in the trap, the Doppler broadening due to γ -decays of the excited daughter state in flight, and a constant background, also folded with the exponential decay. The distribution of the kinetic energy of the ions in the decay trap is unknown for this indium measurement, but the average kinetic energy in the trap can be estimated to $\mathcal{O}(\text{eV})$, based on the trap potential necessary to trap all ions. This will result in a thermal Doppler broadening of $\mathcal{O}(20 \text{ eV})$, i.e. an additional increase of the retardation voltage up to which recoil ions can be detected of $\mathcal{O}(10 \text{ V})$. In addition to the minimal charge state $q_{min} = 2$ also higher charge states q may be present, when taking electron shake-off into account. They contribute to the spectrum below $U_{ret} = E_{max}/q$ accordingly. Close to the theoretical endpoint at $E_{max} = 196$ eV, i.e. $U_{max} = E_{max}/q_{min} = 98$ V, the data overshoot the calculation somewhat, showing that a more complex model is needed to correctly describe the data. The effects leading to deviations from the calculations still have to be understood in detail and have to be minimized for future measurements. At present they lead to increased systematic uncertainties for the analyses discussed in the next section.

An in-depth analysis of the measured recoil spectrum is not possible due to several experimental artifacts:

i) transmission losses due to non-ideal acceleration and focussing potentials, caused by discharges in the acceleration section and at the detector; ii) a significant dead time of the detector, different for different times in the measurement cycle, due to the ions which were shot directly onto the detector; iii) the limited number of retardation steps that were taken for this first measurement of a recoil energy spectrum. This number is not sufficient for fitting all free parameters.

After the measurements with ^{124}In additional measurements were performed with a β and a γ source each at the center of the decay trap (viz. ^{90}Sr and ^{60}Co). These resulted in mostly flat spectra [40], *i.e.* totally different spectral shapes than the one shown in fig. 5, confirming that the ions measured with ^{124}In in the decay trap were not caused by spurious effects but stem from β -decays in the decay trap [40].

4.3 Properties of the ion cloud in the decay trap

Besides the confirmation of the observation of recoil ions from the decay trap, several experimental parameters which influence the performance and the achievable sensitivity of WITCH can be deduced from the above measurements. These are: i) the half-lives of the decaying isotopes and their storage time in the decay trap, which yield information about the proper operation of the trap; ii) the number of ions in the ion cloud, which, together with the signal-to-noise ratio, is important for the statistics of the measurement and therefore the achievable sensitivity of WITCH; iii) the size of the ion cloud, which influences the size of the image of the recoil ions on the detector and iv) the alignment of the whole set-up from the traps to the detector.

4.3.1 Half-life and losses from the ion cloud

The count rate during the measurement of one trap load with constant retardation potential should show a decrease corresponding to the half-life of the isotope investigated. In the present case a mixture of ^{124}In and ^{124m}In is measured and the observed half-life is determined by their relative abundance in the ion cloud. An additional decrease of the count rate beyond what is expected from the half-life of the radioactive decay would be a sign of a loss of ions from the decay trap and would lead to significant systematic uncertainties for the recoil energy spectrum for the measurement cycle discussed above. Recoil ions with low energies are measured early in the measurement cycle and those with high energy late in the cycle. Any loss of ions from the trap during the measurement cycle, *i.e.* during one trap load, would lead to a lower efficiency for high recoil energies than for low recoil energies. This would induce a change of the shape of the recoil energy spectrum and thus of the β - ν angular distribution that is extracted from it.

Table 1 shows the experimentally determined decay constants for the *off-on* and *off-off* measurements shown in fig. 2 for the signals coming from the cooler trap in

Table 1. Fits of the exponential decay $N(t) = N_0 e^{-\lambda t}$ for the *off-on* and *off-off* measurements of fig. 2 (top panel). In the time interval $[0\text{ s}, 1.4\text{ s}]$ the events stem from decays in the cooler trap, in $[1.5\text{ s}, 4.7\text{ s}]$ from decays in the decay trap. Events from the decay trap were only evaluated in the interval $[3\text{ s}, 4.7\text{ s}]$. All four regions should show the decay constant of a mixture of the two indium isomers. The uncertainties shown are statistical only.

Meas.	Region	$N_0 [1/50\text{ ms}]$	$\lambda [\text{s}^{-1}]$	χ^2/ν
<i>off-off</i>	$[3\text{ s}, 4.7\text{ s}]$	18020 ± 260	0.182 ± 0.004	0.98
<i>off-on</i>	$[3\text{ s}, 4.7\text{ s}]$	5340 ± 230	0.205 ± 0.012	2.5
<i>off-off</i>	$[0\text{ s}, 1.4\text{ s}]$	6635 ± 37	0.195 ± 0.007	1.5
<i>off-on</i>	$[0\text{ s}, 1.4\text{ s}]$	9749 ± 71	0.201 ± 0.010	3.7

the first 1.4 seconds as well as from the decay trap in the last 1.65 seconds of the measurement cycle, when the MCP had recovered from the dead time caused by the ions that were shot onto it during the transfer to the decay trap. For this latter case ($[3\text{ s}, 4.7\text{ s}]$) the measurement *off-on* consists of background only (β -particles according to PHD and position distribution), since all recoil ions will be reflected by the retardation potential. Correspondingly, the measurement *off-off* consists of both signal (ions) and background (β -particles). The values of the reduced χ^2 indicate that some as yet unknown systematic uncertainties may be present, which we take into account by adjusting the error bars of the fitted values for the three periods with $\chi^2/\nu > 1$ by a factor of $\sqrt{\chi^2/\nu}$ for the calculation of the weighed average, with ν being the number of degrees of freedom.

The four measured decay constants are consistent with each other and result in a weighed average of $\bar{\lambda} = 0.186 \pm 0.004\text{ s}^{-1}$, corresponding to a half-life of $t_{1/2} = 3.73 \pm 0.08\text{ s}$ and an abundance ratio of ^{124g}In ($\lambda = 0.223 \pm 0.008\text{ s}^{-1}$) to ^{124m}In ($\lambda = 0.187 \pm 0.011\text{ s}^{-1}$) of 0.00 ± 0.33 (see footnote²). Note however, that the accuracy of this ratio is limited by the uncertainties of the literature values of the half-lives and thus does not allow an unequivocal determination of the relative abundances.

The experimental decay constant of $\lambda_{ion} = 0.182 \pm 0.004\text{ s}^{-1}$ for the case when ions dominate the count rate (first line in table 1) is consistent with the smallest possible decay constant from ^{124}In , *i.e.* $\lambda(^{124m}\text{In}) = 0.187 \pm 0.011\text{ s}^{-1}$, consistent with small or negligible losses from the trap. A conservative upper limit on the losses from the decay trap can then be calculated to be $1/N_0 dN_{DT}/dt < 0.026\text{ s}^{-1}$ ($CL = 99.5\%$), *i.e.* less than 2.6% per second³.

² Since both half-lives are very similar we approximate $\bar{\lambda} = k\lambda_g + (1-k)\lambda_m$ with k the abundance of the ground state.

³ At a later time a test measurement with argon ($\Phi_{Ar} = 15.8\text{ eV}$) was performed. As with the indium, the argon was cooled by helium buffer gas in the cooler trap. In contrast to the measurements with indium, the argon showed a rapid charge exchange in the cooler trap with an overall half-life of $t_{1/2}^{tot}(^{35}\text{Ar}) \approx 8\text{ ms}$ while the half-life for the β -decay is $t_{1/2}(^{35}\text{Ar}) \approx 1.78\text{ s}$. This charge exchange problem for argon has been resolved in the meantime by a reduction of the rest gas level in the traps.

4.3.2 Number of ions in the ion cloud

A high source strength, *i.e.* a large number N_{DT} of radioactive ions that are stored in the decay trap, is important to reach low statistical uncertainties. From the normalization constants $N_0(on)$ and $N_0(off)$, which give the event numbers in an interval of 0.05 s, follows the initial count rate in the MCP, $\frac{dN_{MCP}}{dt} = 3650 \pm 80 \text{ s}^{-1}$ (at $t = 1.5 \text{ s}$, the time of the filling of the decay trap), per trap load. This count rate is related to the initial number of ions in the decay trap N_{DT} as

$$\frac{dN_{MCP}}{dt} = \epsilon_{\Omega} \cdot \epsilon_{Trans} \cdot \epsilon_{MCP} \cdot \lambda_{ion} \cdot N_{DT} \quad (1)$$

with $\lambda_{ion} = 0.182 \pm 0.004 \text{ s}^{-1}$ the decay constant measured for the ions, $\epsilon_{\Omega} = 0.5$ for the solid angle of the decays emitted into the forward direction, $\epsilon_{Trans} = 0.56 \pm 0.05$ the transmission probability for doubly charged recoil ions from the decay trap (depth of $\approx 8 \text{ V}$) to the detector, estimated from simulations for an ion cloud radius of 2 mm (see sect. 4.3.3), and $\epsilon_{MCP} = 0.523$ measured for a comparable MCP [37] and close to the open area ratio of 0.55, *i.e.* the ratio of the area of the MCP covered by channels to its total area, which defines the sensitive area of an MCP. The probability for the creation of the different charge states does not need to be included since the measurement was performed at zero retardation voltage and all charge states are transmitted through the spectrometer to the detector.

Using these numbers results in an average trap load of $N_{DT} = (1.4 \pm 0.2) \cdot 10^5$ indium ions. For this estimate the presence of higher charge states, which have a lower escape probability from the decay trap (*i.e.* a lower ϵ_{Trans}), has been neglected since they contribute only at the 10–20% level. This results in an additional systematic uncertainty of the order of 10% for N_{DT} . 10^5 ions per trap load is a reasonable source strength for test measurements but is an order of magnitude smaller than the design value of 10^6 ions. Thus, several features of the set-up still have to be optimized for a precision measurement, as *e.g.* the injection efficiency into the cooler trap, which was measured to be just $\approx 10\%$ for this initial experiment.

4.3.3 Size of the ion cloud

The size of the ion cloud in the decay trap is one of the factors that determine whether all recoil ions are focussed onto the detector and what their spot diameter on the detector is. The decay trap was operated in box trap mode, *i.e.* the endcap electrodes were at the trapping potential ($\approx 8 \text{ V}$) and the inner electrodes all at the same low potential (0 V), leading to a longitudinal ion cloud size of $\approx 100 \text{ mm}$. The radial extent of the ion cloud can be inferred from the size of the ion spot on the detector by a comparison with tracking simulations for different ion cloud sizes. Figure 6 shows the comparison of the simulated spot sizes with the measured one. For the simulations a cylindrical ion cloud of homogeneous density

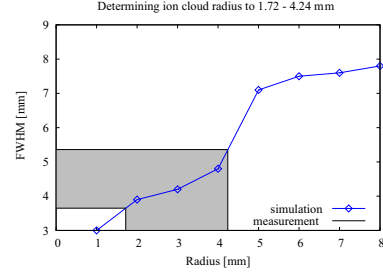


Fig. 6. FWHM of the simulated position distribution of ions on the detector as a function of the radius of the ion cloud in the decay trap. The shaded area marks the FWHM of the experimental position distribution. Comparing both yields a radius of the ion cloud in the range [1.5 mm, 4.3 mm].

was assumed since a detailed model for realistic density distributions at different trap potentials and numbers of ions still has to be developed. The simulations are for ions of charge state $q = 2^+$ and use a recoil spectrum with the maximum endpoint energy only. The comparison results in an estimate of the ion cloud radius in the range [1.7 mm, 4.3 mm]. Again, as already obvious from fig. 5 and as stated in the previous section, the effect of higher charge states will modify these numbers. According to their contribution this systematic uncertainty will be in the 20% range. In any case the ion cloud size is larger than the radius of the differential pumping barrier of 1.5 mm, which determines the initial maximal size of the ion cloud, and indicates an additional increase of the ion cloud size during storage in the decay trap. The simulated position distributions for the ions and the β -particles for a radius of 3 mm are shown in fig. 4.

4.3.4 Signal to noise ratio

The ion cloud size also determines the signal to noise ratio, since in the ideal case all recoil ions are focussed onto the detector whereas the number of β -particles that hit the detector decreases with increasing ion cloud size because electrons with larger starting radii have a smaller probability of hitting the detector and will eventually not hit the detector anymore. The signal to noise ratio can be extracted from the fit results shown in table 1. For the *off-on* measurement the normalization constants for the signal region are $N_0(on) = 5340 \pm 230$ for 90 trap loads and $N_0(off) = 18020 \pm 260$ for 60 trap loads, yielding a signal to noise ratio of $S/N = 4.06 \pm 0.23$.

The background can be further subdivided into background from β -particles, which are distributed across the full detector surface, and background due to decays on the detector surface of those ions that were shot onto the detector upon transfer, which appear as a peak close to the center of the detector (*on* measurement, fig. 3, bottom panel). These two contributions can be separated by

counting the events outside and inside a circle centered around the strongly peaked maximum in the position distribution during the *on* measurement. Inside a circle of radius 7.5 mm there are 15670 events compared to 15283 events in between 7.5 mm and 23.6 mm, the radius of the MCP detector. When the β background of 15283 events is extrapolated to radii < 7.5 mm, this results in a total number of events due to β -particles of 17016 for the full MCP area and a number of events due to decays on the detector of 13937. This calculation assumes a flat distribution of the β background across the detector surface. However, simulations show that the β background has a slight maximum in the center of the detector, depending on the size of the ion cloud. Still, the numbers above show the size of the dominant effects that determine the signal to noise ratio. Using the numbers as they are indicates that $\approx 13937/(13937 + 17016) = 45\%$ of the background are due to decays on the detector. When correcting both the background and the signal count rates for the *off* measurement with this fraction, the signal to noise ratio can be $S/N \approx 5.2$, assuming that the trapping efficiency is improved and no radioactive ions get shot onto the detector.

4.3.5 Alignment traps detector

As already mentioned, the narrow peak for the *on* distribution in fig. 3 (bottom) at the center of the detector corresponds to the decay of radioactive ions that were shot onto the detector due to a trapping efficiency $< 100\%$. This peak can be used as a measure of the alignment and focussing properties of the WITCH set-up: the ions were shot through the differential pumping barrier, which is mechanically centered along the axis of the traps. The ions have predominantly longitudinal kinetic energy, travel parallel to the B -field and see a cylindrically symmetric electric field, since they fly close to the symmetry axis.

The spot of the ions is located at a distance of $\Delta r = 2.2 \pm 0.1$ mm from the center of the detector. With a distance of 2.644 m between the center of the decay trap and the detector this corresponds to an angle of $0.047^\circ \pm 0.002^\circ$.

5 Conclusion

The WITCH experiment has been set up at ISOLDE to measure the recoil energy spectrum after β -decay, from which the β - ν angular correlation will be determined for a search for scalar weak interaction. In a first measurement with the radioactive ions ^{124}gIn and ^{124}mIn it has been shown that recoiling ions from the Penning trap can be efficiently detected, thus demonstrating the experimental principle. Especially, up to 10^5 ions have been stored in one trap load in the decay trap with no significant losses during one trap load, within the accuracy of the measurement. The radius of the ion cloud was estimated to be in the range [1.7 mm, 4.3 mm]. The recoil ions from the β -decays in the trap were transmitted through the

spectrometer and focussed onto the detector which is consistent with simulations for the settings used during the measurement. It was shown that the events detected are recoil ions and a first recoil ion energy spectrum was measured in coarse steps and with a signal-to-noise ratio of $S/N = 4$, which can still be improved.

After having observed recoil ions at WITCH, the set-up is now being further improved and systematic effects are being studied in preparation of a precise determination of the β - ν angular-correlation coefficient a . The experimental improvements include the elimination of discharges in the spectrometer and the reacceleration section, increasing the efficiencies of the traps that do not capture all ions but let some get transmitted onto the detector, and the reduction of charge exchange of stored ions with high ionization potential. For this purpose a number of spectrometer electrodes have been remachined, all electrodes have been electropolished, a new set of Penning trap electrodes has been installed, all materials incompatible with the desired UHV conditions have been removed and getter vacuum pumps based on non-evaporative getter have been installed. Recently, also a new control system has been installed which facilitates a faster and better tuning of the set-up [43].

For a precision analysis of the recoil spectrum the systematic problems of the set-up have to be understood as well. To this end, simulations for the traps and the spectrometer (see *e.g.* [44]) as well as test measurements are ongoing. In addition, physics effects like the charge state distribution after β -decay (see *e.g.* [42, 45]) and the decay of a potentially unstable daughter in flight will be investigated in the future.

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Appendix E

Decay Schemes

The decay schemes of isotopes used throughout this work are listed in this appendix.

- ^{35}Ar is the prime physics candidate.
- ^{124}In and $^{124\text{m}}\text{In}$ have been used for the first measured recoil ion energy spectrum at WITCH.
- ^{60}Co is used as an offline γ source.
- ^{137}Cs is used as an offline γ source.
- ^{241}Am is used as an α source to characterise the detector and was also used once for the characterisation of the ionisation effect in the spectrometer. The decay scheme of ^{241}Am is not listed here as it contains many transitions. The most important γ transitions have energies of 59.5 keV and 103 keV. The corresponding α endpoint energies are 5485.56(12) keV and 5442.80(13) keV respectively.
- ^{90}Sr (and ^{90}Y) is used as an offline β^- source.
- ^{22}Na is proposed as an offline β^+ source.

All figures have been taken from [NND, 2011].

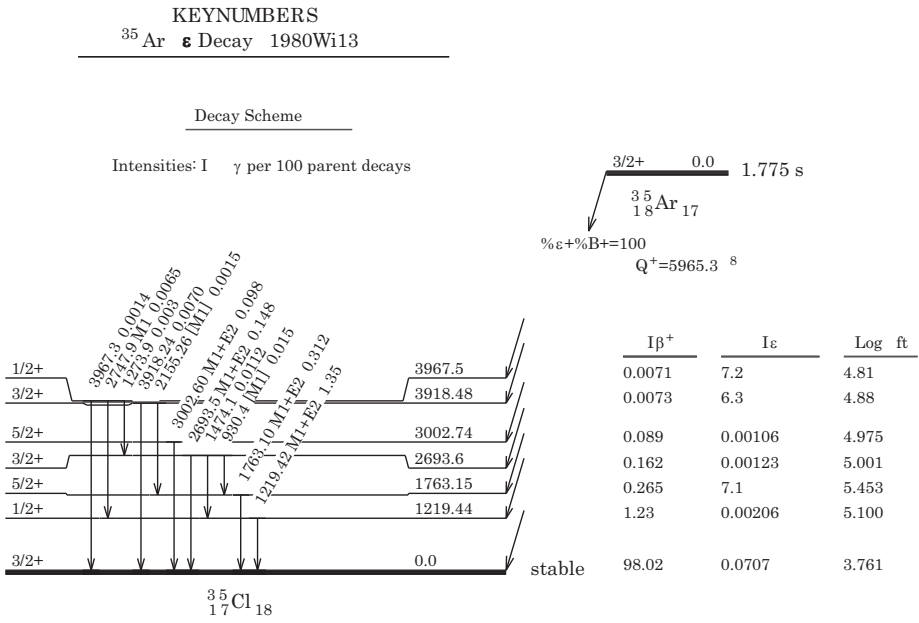


Figure E.1 – Decay scheme of ³⁵Ar.

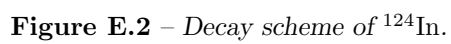
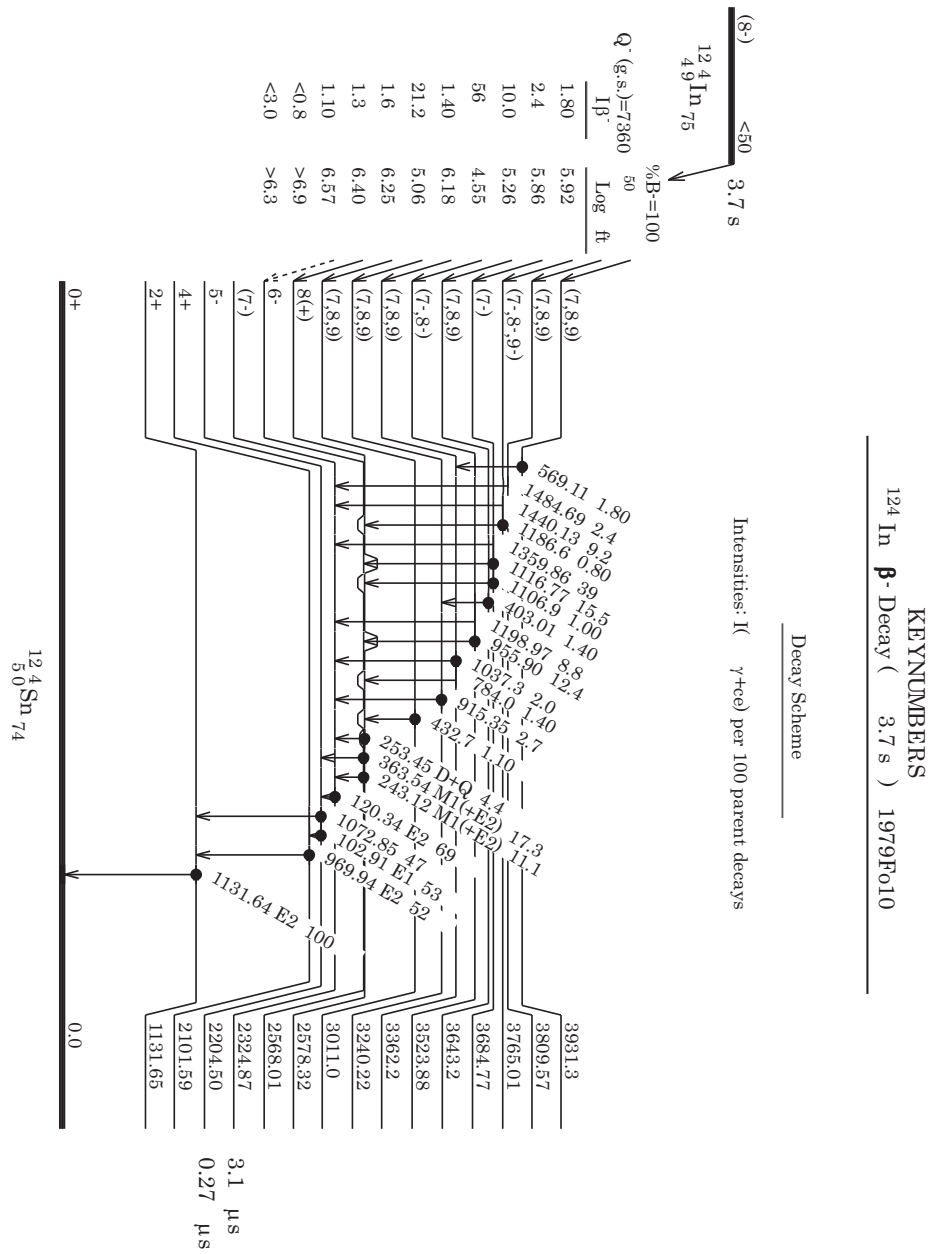
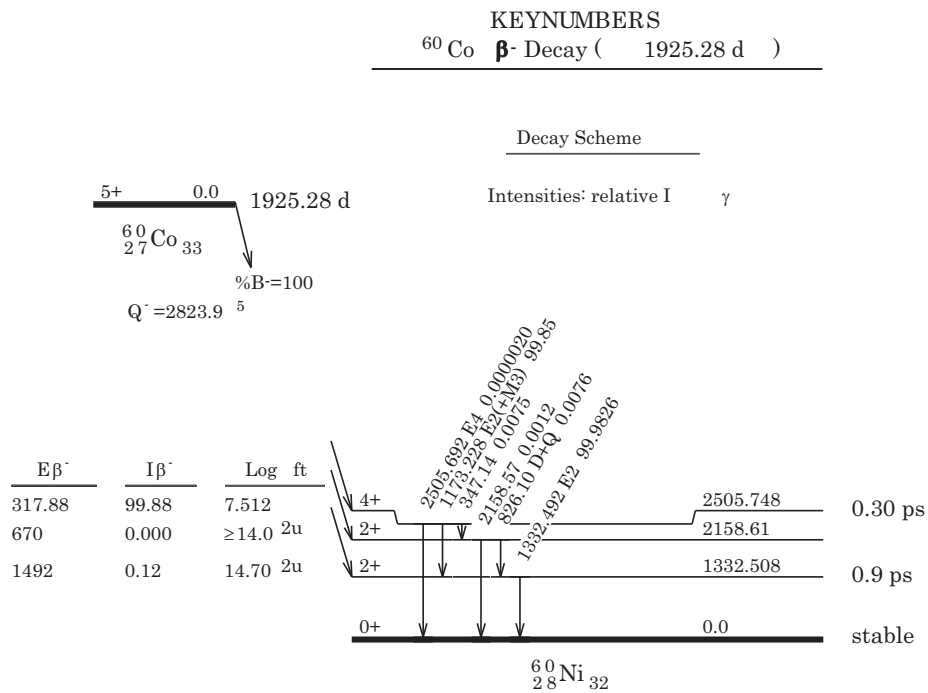
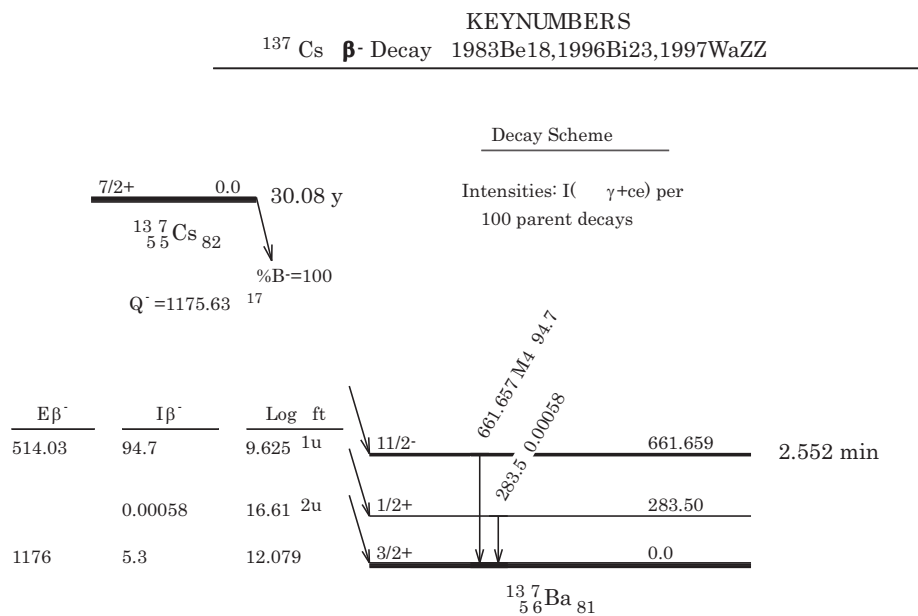


Figure E.2 – *Decay scheme of ^{124}In .*



Figure E.4 – Decay scheme of ^{60}Co .Figure E.5 – Decay scheme of ^{137}Cs .

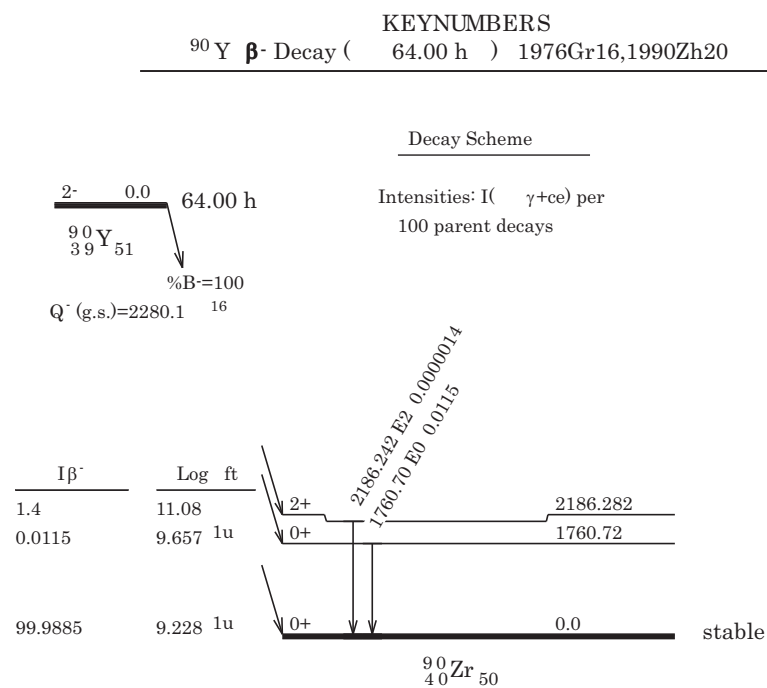


Figure E.6 – Decay scheme of ^{90}Y . The decay of ^{90}Sr is a pure β^- transition with an endpoint energy of 246.0(14) keV.

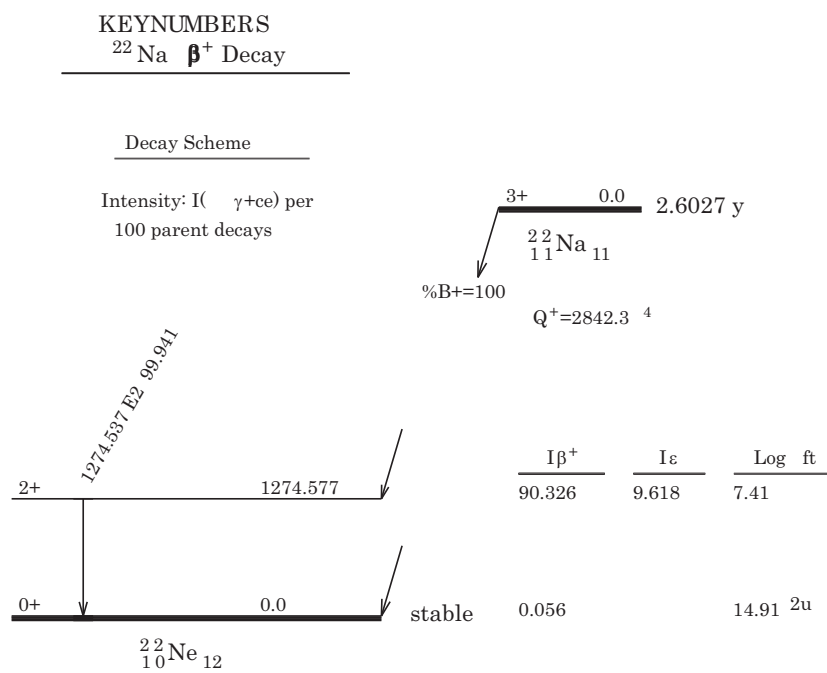


Figure E.7 – Decay scheme of ^{22}Na .

Publication List

- **Computer Controls for the WITCH Experiment**
M. Tandecki, D. Beck, M. Beck, H. Brand, M. Breitenfeldt, V. De Leebeeck, P. Friedag, A. Herlert, V. Kozlov, J. Mader, S. Roccia, G. Soti, E. Traykov, S. Van Gorp, F. Wauters, Ch. Weinheimer, D. Zákoucký, N. Severijns
Nuclear Instruments and Methods A, 629 (2011) 396–405
- **Ft values of the $T = 1/2$ mirror transitions**
N. Severijns, M. Tandecki, T. Phalet and I.S. Towner
Phys. Rev. C 78, 055501 (2008)
- **Simbuca, using a graphics card to simulate Coulomb interactions in a Penning trap**
S. Van Gorp, M. Beck, M. Breitenfeldt, V. De Leebeeck, P. Friedag, A. Herlert, T. Iitaka, J. Mader, V. Kozlov, S. Roccia, G. Soti, M. Tandecki, E. Traykov, F. Wauters, Ch. Weinheimer, D. Zákoucký, N. Severijns
Nuclear Instruments and Methods A, 638 (2011) 192–200
- **First detection and energy measurement of recoil ions following beta decay in a Penning trap with the WITCH experiment**
M. Beck, S. Coeck, V. Yu. Kozlov, M. Breitenfeldt, P. Delahaye, P. Friedag, F. Glck, M. Herbane, A. Herlert, I.S. Kraev, J. Mader, M. Tandecki, S. Van Gorp, F. Wauters, Ch. Weinheimer, F. Wenander, N. Severijns
European Physics Journal A, 47 (2011) 1–9
- **A compact radio frequency quadrupole for ion bunching in the WITCH experiment**
E. Traykov, M. Beck, M. Breitenfeldt, P. Delahaye, V. De Leebeeck, P. Friedag, A. Herlert, N. Geeraert, W. Heirman, P.-I. Lne, J. Mader, S. Roccia, G. Soti, M. Tandecki, M. Timmermans, J. Thiboud, S. Van Gorp, F. Wauters, C. Weinheimer, D. Zákoucký, N. Severijns
Accepted for publication in Nuclear Instruments and Methods A, DOI: 10.1016/j.nima.2011.03.024
- **Precision measurements of the Co-60 beta-asymmetry parameter to search for tensor currents in weak interactions**
F. Wauters, I. Kraev, D. Zákoucký, M. Beck, V. De Leebeeck, V. V.

Golovko, V. Yu. Kozlov, T. Phalet, G. Soti, M. Tandecki, I. S. Towner, E. Traykov, S. Van Gorp, and N. Severijns
Phys. Rev. C 82, 055502 (2010)

- **A GEANT4 Monte-Carlo simulation code for precision beta spectroscopy**

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Nuclear Instruments and Methods A 609 (2009) 156-164

- **Performance of silicon PIN photodiodes at low temperatures and in high magnetic fields**

F. Wauters, I.S. Kraev, M. Tandecki, E. Traykov, S. Van Gorp, D. Zákoucký, N. Severijns
Nuclear Instruments and Methods A 604 (2009) 563-567

- **Beta asymmetry parameter in the decay of In-114**

F. Wauters, V. De Leebeeck, I. Kraev, M. Tandecki, E. Traykov, S. Van Gorp, N. Severijns, D. Zákoucký
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- **Ab initio simulations on the behaviour of small ion clouds in the WITCH Penning trap system**

S. Coeck, B. Delauré, M. Herbane, V. Yu. Kozlov, I.S. Kraev, M. Tandecki, F. Wauters, M. Beck, P. Delahaye, A. Herlert, S. Sturm, N. Severijns
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N. Severijns, A. A. Belyaev, A. L. Erzinkyan, P. -D. Eversheim, V. T. Filimonov, V. V. Golovko, G. M. Gurevich, P. Herzog, I. S. Kraev, A. A. Lukhanin, V. I. Noga, V. P. Parfenova, T. Phalet, A. V. Rusakov, M. Tandecki, Yu. G. Toporov, C. Tramm, E. Traykov, S. Van Gorp, V. N. Vyachin, F. Wauters, D. Zkouck, and E. Zotov
Phys. Rev. C 79, 064322 (2009)

Conference Contributions

- **WITCH, a Double Penning Trap Experiment for Weak Interaction Studies**
Oral contribution at conference
TCP 2010 (Trapped Charged Particles and fundamental physics), Saariselkä (Finland), 12-16/04/2010
- **WITCH: Control System**
Oral contribution at workshop
CS-Framework workshop GSI, Darmstadt (Germany), 19/02/2010
- **WITCH: Recent Developments**
Oral contribution at conference
Joint Laser-Trapspec Workshop, La Londe les Maures (France), 29 Sep - 01/10/2008
- **WITCH: a Double Penning Trap Experiment for Weak Interaction Studies**
Oral contribution at conference
PANIC 2008 (Particles And Nuclei International Conference), Eilat (Israel), 9-14/11/2008
- **WITCH: First measurements and recent developments**
Oral contribution at conference
ISOLDE Workshop and Users meeting, Geneva (Switzerland), 17-19/12/2007
- **WITCH: mass resolving capabilities of the Penning traps**
Oral contribution at research school
Fantom Research School, Symmetries and symmetry violation, Ghent (Belgium), 24/05/2007
- **WITCH: a tool to search for physics beyond the standard model**
Oral contribution at workshop
General Scientific Meeting of the Belgian Physical Society, Antwerp (Belgium), 30/05/2007
- **WITCH: A trap experiment to study weak interaction properties and more**

Oral contribution at research school

*Fantom Research School, Particles in traps: physics and technology,
Groningen (The Netherlands), 24/05/2007*

- **WITCH: Status & Future**

Oral contribution at workshop

*BriX workshop (Interuniversity Attraction Poles (IAP) Programme),
Leuven (Belgium), 23/01/2007*

- **Mirror nuclei in the study of weak interaction properties**

Oral contribution at research school

*Fantom Research School, Physics with radioactive beams,
Leuven (Belgium), 05/11/2006*

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